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THE DIFFERENCES AMONG GLOBULAR CLUSTERS

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THE AREAS OF DIFFERENCE AMONG GLOBULAR CLUSTERS

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I think that no one, since the start of cluster gazing centuries ago, has ever assumed that all galactic clusters are just alike. Can you imagine, for example, anyone saying that if the Pleiades were three times closer they would look just like the Hyades? The differences among galactic clusters are so obvious that it does not occur to anyone to lay down the same specifications for each and every cluster.

But many astronomers in the past have assumed that globular clusters are practically all alike because they were more impressed with the individual similarities of these clusters than with their differences. Consequently, particularly in the first quarter of the present century, globular clusters were studied under the assumptions that a rule which applied to one, applied to all. For example, we read that the "curve apparently justifies the hypothesis that all globular clusters are of nearly the same linear dimensions." These generalizations were quite in order a quarter of a century ago. In fact, when used by Harlow Shapley (1918) they gave a better picture of the size and form of our galaxy and of the space distribution of globular clusters than ever previously obtained. They are, however, no longer

tenable. Superficially many globular clusters do look alike. But over and over again in recent years observations have begun to show the differences which exist among them. And these differences have a very wide range.

Some of the more important of these differences will be discussed in detail by my colleagues who follow in this symposium. My purpose is to outline the areas in which globular clusters have been found to be noticeably different. I should emphasize, however, how incomplete our knowledge still is. For example, there are at present 118 clusters accepted as globular, belonging to our galaxy or not belonging to some other galaxy (Sawyer-Hogg 1959). Magnitudes for individual stars, either bright stars or variables, have so far been determined for only about two-thirds of these. That leaves a third of the known globulars for which we can say practically nothing about the individual stars.

One of the first steps in the recognition of the individual character of globular clusters was the classification scheme of Shapley and Sawyer (1929), in which clusters were assigned Roman numbers I-XII in proportion to their degree of central concentration, with a special GP category

for several clusters noticeably lacking in giant stars. From this classification of globular clusters, it appeared that there was a correlation of the absolute magnitudes of the 25 brightest stars with the cluster class, ranging from -1.34 for Class I to -0.92 for Class XII, as based on a zero absolute magnitude for the RR Lyrae variables. In addition, the giant-poor clusters had their 25 brightest stars only 0.44 mag. brighter than the RR Lyrae variables. This spread in the magnitudes of the brightest stars from cluster to cluster was emphasized recently by Rosino (1957) in his investigation of the cluster Palomar 13, in which the four RR Lyrae variables are actually the brightest stars, having a mean median photographic magnitude of 18.0 , while the 6th brightest star (usually assumed to be the brightest actual cluster member) is only 18.1 .

The absolute magnitude of a globular cluster is certainly one of its most significant characteristics, and the change in our appreciation of the spread in absolute magnitudes of these clusters exemplifies our change in attitude as a whole. Not many years ago (Shapley 1920) it was considered that, since more than half the globular clusters had absolute magnitudes between -8.3 and -9.3 , the distances might be derived by assuming a similarity of total light emission in globular clusters. It is now obvious that there is a range of at least five magnitudes in this quantity. The highly accurate schraffierkassette magnitudes by Christie (1940) have confirmed the spread, instead of diminishing it. Absolute magnitudes range downwards from about -10 for the two outstanding clusters Omega Centauri and 47 Tucanae to about -5 for feeble clusters like NGC 7492 and NGC 4147.

The absolute magnitudes will of course be related to the masses. That there is a spread in masses is obvious, but just how great is not so readily determined, as there is substantial disagreement in mass determinations. The recent extensive calculation by Matsunami (1959) and his colleagues in Tokyo. gives masses ranging from 780,000 solar masses for M53 to 3000 for NGC 6366. Gascoigne and Burr (1957) estimate the mass of Omega Centauri at 2,000,000 suns, and that of 47 Tucanae at 1,300,000, while Kurth (1951) set M22 at 6,700,000. At the other end of the scale Mrs. Burbidge and Sandage (1958) estimate the mass of the intergalactic globular clusters Palomar 3 and Palomar 4 at 1.1×10^4 and 1.8×10^4 solar masses, respectively. One of the best-determined globular cluster masses is

that of M3, in which the estimate by Sandage (1957) of the mass of 2.45×10^5 , from the luminosity function correlates well (from the luminosity standpoint) with a dynamical mass of $1.4 \pm 0.7 \times 10^5$ obtained for M92 by Schwarzschild and Bernstein (1955) from the velocity dispersion measures of O. C. Wilson and Miss Coffeen (1954). Apparently globular cluster masses may differ by a factor of at least fifty, and possibly a hundred.

With so much difference of opinion about the masses, and so much range in them, it is obvious that even greater uncertainty exists in estimating the central density and its range. Near the center of an average globular cluster the density may be about 50 stars per cubic parsec, but if we accept the computations of Gascoigne and Burr, densities in 47 Tucanae and Omega Centauri would be hundreds or even thousands of times this.

Also related to absolute magnitudes and masses are the diameters. A wide variety of methods has been used to determine apparent diameters of globular clusters—small-scale plates, extra-focal images, star counts, or even the distribution of RR Lyrae variables. Modern theories of cluster dynamics indicate that the diameter of a cluster will be correlated with its total mass, and therefore, with its absolute magnitude. A great spread in linear diameters of globular clusters is therefore expected, and is observed, ranging from the determination by Lindsay (1956) of 190 pc for Omega Centauri down to the value of Sandage and Walker (1955) of only 16 pc for the feeble little cluster NGC 4147. Lohmann (1953) has shown statistically that the linear diameter of a globular cluster is correlated with its distance from the galactic center, in the sense that clusters 25,000 pc from the center are 30 per cent larger than those at only 10,000 pc. The diameters of the intergalactic clusters of small mass, Palomar 3 and 4, are shown by Burbidge and Sandage (1958) to be anomalously large at 80 and 90 pc respectively, indicating that these clusters have never come within 9000 pc of the galactic center.

The subject of diameters leads immediately to the related one of ellipticities. This is one of the areas in which globular clusters appear least diverse. Superficially most globular clusters do not show a marked degree of ellipticity, though several, especially NGC 6273, are conspicuously non-spherical. The detailed analyses by Kholopov (1952) indicate that the ellipticity is definitely correlated with the limiting magnitude of

the stars used in determining it, and this seems to be corroborated in the work on Omega Centauri by Lindsay (1956). Kholopov finds that globular clusters consist of a number of zones, each characterized by certain values of the average density gradient. The orientation of the ellipsoid of equal apparent density in the inner regions may differ from the orientation in the outer regions. Thus the subject becomes a very complicated one and incapable of brief summarization.

A most important characteristic of globular clusters is their color-magnitude diagrams. These were early shown by Shapley to be markedly different from those of galactic clusters. This distinction still remains a vital fact which aids in assigning problem clusters like NGC 2682 and 7789 to the galactic cluster category. Nevertheless, important differences among globular clusters themselves are now beginning to be evaluated. As color-magnitude diagrams will be discussed later in the symposium, I will not carry the topic further.

One great difference among globular clusters which has been obvious from the start is the difference in number of variables from cluster to cluster. The great rich clusters like M3 with almost 200, and Omega Centauri with 165, emphasize the scarcity in other bright clusters like M10 and 12 in which only three and one are known, respectively, despite thorough searches by experienced people (Sawyer 1955). In the 80 clusters searched so far, about 1500 variables have been found. Only 4 clusters appear to be lacking them.

Not merely is there a great difference in the number of variables in individual globular clusters, but the types of variables present also differ. Though 90 per cent of the variables in globular clusters can be classed as RR Lyrae stars, it may surprise you to realize (because the mental association of cluster-type variables with globular clusters is so strong), that 50 per cent of the globular clusters searched have to date no identified RR Lyrae stars. Of course the presence or absence of variables and their types is dependent on the color-magnitude diagram (Arp 1955), and I shall leave any further discussion of this point for the later speakers, as well as the problem of uniformity of absolute magnitudes for the RR Lyrae stars.

A curious difference among clusters is that of the maximum frequency of period of the RR Lyrae stars. This maximum differs markedly

from cluster to cluster. Some clusters have a double maximum at periods around one-third and two-thirds of a day, while others have a single maximum at periods around half a day (Oosterhoff 1939; Sawyer 1944). The cause is not yet fully known, though Sandage has suggested that it may be related to the absolute magnitude of the horizontal branch.

One of the most exciting new points of difference among globular clusters is in their metal content, as shown in their integrated spectra. While most globular clusters show the weak metallic lines which are typical of high-velocity stars and which are assumed to represent an early origin in the universe, Mayall (1946) and Morgan (1956) have found a notable group with metallic line strengths comparable even with our sun. This important point will be discussed more fully in later papers presented during the Symposium.

Now, having briefly mentioned most of the essential differences among globular clusters *per se*, I would like to draw your attention to some of the differences which arise as an effect of distribution.

One such difference will be caused by interstellar absorption. Because a number of rich and massive clusters like M3 and M13 are in high galactic latitudes, I think it is often forgotten that two thirds of the globular clusters known in our galaxy today are within 20 degrees of the galactic equator. This means that most globular clusters are exceedingly vulnerable to the effects of interstellar absorption. You will appreciate how greatly our understanding of the cluster is affected by the correction applied for absorption when I tell you that distances actually published within the last ten years for NGC 6171 (M107) range from 2.6 (Lohmann 1952) to 21.2 kpc (Zagar 1954), and for NGC 6517 from 9.1 to 50.0 kpc, according to the allowance made for absorption. Obviously, until we have brushed away the entangling web of interstellar material from our observations of globular clusters we can have at best only a foggy notion of their similarities and differences. Accurate colors in several wave lengths, discussed by Dr. Mayall, are of the greatest value in helping our understanding of the clusters.

An important difference, most inadequately investigated, is the obvious streaks of dark nebulosity in certain globular clusters, in high or low latitudes. Among high latitude clusters, they are very conspicuous in M13, M3, and M2, and less marked in M5 and M15. Whether or not the dark

streaks in M13 are the optical result of chance star chains has been a controversial subject for 60 years. Many pages have been written to prove that they are illusions, due to chance groupings of stars, or to show that it is not possible for diffuse nebulosity to exist in a globular cluster. As a person who has handled large-scale plates of globular clusters steadily for over thirty years, I stand firmly on the side that the dark lanes in the Hercules cluster and certain others are real patches of nebulosity, and are not effects of random grouping of stars. Whether the nebulosity is actually a part of the cluster, or is a wisp of interstellar material between us and the cluster, I have no conviction. But if there are small wisps of material in high galactic latitudes, can you name any other object against which they would show so well in projection as a globular cluster? Against an external galaxy it would be taken for granted that they were part of it. The time interval of large-scale cluster photographs may even now be getting sufficiently large that relative motion of the dark lanes with respect to the cluster stars, or relative dimming or brightening of cluster stars contiguous to the dark lanes, may be measurable.

Another contrast in globular clusters caused by their galactic positions is the large range in radial velocities, which are shown by Mayall (1946) to be from 360 km/sec of approach for NGC 6934 to 291 km/sec of recession for NGC 1851. This great difference is largely an effect of the sun's motion around the galactic center.

Then in the differences caused by location of clusters we have those which occur between clusters associated with different systems. For example the contrast between the globular clusters of our galaxy and those of the Magellanic Clouds are discussed in detail in Dr. Thackeray's paper. Sandage and Wallerstein have compared NGC 6356 near the galactic nucleus with halo clusters; Dr. Morgan's paper discusses these positional differences further.

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PHOTOELECTRIC PHOTOMETRY OF GALACTIC AND EXTRAGALACTIC STAR CLUSTERS

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Photoelectric observations are reported for a total of 187 star clusters: 67 globular and 28 open in the Galaxy, 11 in the Magellanic Clouds, 2 in the Fornax dwarf elliptical, and 79 in the M31 group of galaxies. All were observed in two colors, *P* and *V*, and 117 in an infrared, *I*, color. The three-color measurements were made for all the galactic globular and open clusters, but only for 22 clusters in the M31 group, because of their faintness. Series of graded apertures up to 25' diameter were used for the globular clusters in the Galaxy and in the Clouds, in order to deter-

mine total magnitudes and diameters containing 0.9 the total light.

The two-color photometric system is an ultra-violet-free photoelectric approximation to International, and it is based on 24 NPS stars that include the nine primary standards of Stebbins, Whitford and Johnson (1950). The *V*-magnitudes correspond closely with the International photovisual ones of Seares and Joyner (1945), and they are linearly related to those of Eggen (1955) and of Johnson and Morgan (1953) for $-0.4 < (P - V) < +1.0$. Within this range, and

or a precision of ± 0.03 mag., Johnson and Morgan's $(B-V) = (P-V) + 0.10$. The infrared index $(V-I)$ is based on a system like the infrared part of the R, I one of Kron, White and Gascoigne (1953). Because of the inconvenience of working with the polar primary standards, secondary ones were established in four Harvard C and D regions. In addition to these standards, stars of known spectral type and of negligible space reddening were observed to define the main, giant and dwarf sequences in the two color-index plot of $(P-V)$ vs. $(V-I)$. Lastly, some space-reddened F- and G-type supergiants (Kron 1958) were observed in order to indicate, in the same plot, the reddening line for objects of intrinsic color comparable to clusters.

In the Galaxy, the two color-index plot for all the star clusters indicates that the P, V, I system generally separates the globular from the open clusters, even with considerable space reddening. The points for the redder globular clusters are drawn out in the diagram in a direction closely parallel to the reddening line for the later-type supergiants, and there is some dependence upon spectral type of both the $(P-V)$ and $(V-I)$ color indices. This situation led to estimation of color excesses by taking differences, as a function of spectral type, between the observed colors and bluest-color bounding curves suggested by the colors of clusters in fields showing galaxies. It seemed desirable, however, because of the scarcity of type G0 to G5 clusters in unobscured fields, to use two alternative bounding curves in each color for types F5 to G5. One allowed for a variation of ~ 0.3 mag. in $(P-V)$ or ~ 0.4 mag. in $(V-I)$, the other of only ~ 0.1 mag. in $(P-V)$ or ~ 0.15 mag. in $(V-I)$. For clusters of unknown spectral type, F5 was assumed for those with $b > 20^\circ$, G0 for those with $-20^\circ < b < +20^\circ$, and G5 for those in a group near the direction to the galactic center. The color excesses so determined were then used to obtain the visual absorption from the relationship $A_V = (2.9 \pm 0.2) E_{(P-V)}$, which was obtained from previously published six-color photometry. For the infrared colors, $A_V = (2.3 \pm 0.14) E_{(V-I)}$. Total absorptions and corrected photometric distance moduli, where available, were then obtained for most of the observed galactic globular clusters.

In M31, an effort was made to observe all clusters 16.5 pg mag. and brighter, and particularly all those known outside the main part of the spiral. Two clusters in each of the dwarf companions NGC 185 and 205, and four in M33

were also observed. The measured $(P-V)$ colors range from $+0.02$ to $+1.94$, and, for $(P-V) < +0.50$, there are three clusters in M31, one in NGC 205, four in M33, and they have V magnitudes ranging from 16 to 17. For 24 outlying clusters in M31, the $(P-V)$ colors range from $+0.50$ to $+0.90$. For clusters in M31 with $(P-V) > +0.90$, there is a conspicuous tendency for the redder ones to become fainter. The plot of V vs. $(P-V)$ shows a fairly well-defined, sloping boundary, which suggests that some of the highest luminosity clusters are increasingly dimmed and reddened by interstellar matter in the spiral. From a least squares solution involving eight limiting cases, it was found that $A_V/E_{(P-V)} = 2.50 \pm 0.14$, but the difference of 0.40 ± 0.24 from that obtained from galactic objects is not regarded as significant of different absorbing matter in M31 than in the Galaxy. For the 21 M31 clusters observed in three colors, the $(P-V)$ vs. $(V-I)$ plot is similar to that for the galactic globulars in showing pronounced elongation parallel to a reddening line. Since the outlying, presumably unreddened clusters have $(P-V) = +0.68 \pm 0.12$ (m.e.), a "normal" color index of 0.70 was used to compute color excesses and absorptions for the 13 clusters with $(P-V) > +0.90$; the resulting values of $E_{(P-V)}$ range from 0.1 to 1.2, and A_V from 0.6 to 3.6 mag.

When the corrected colors are collected in intervals of 0.05 in $(P-V)$, the histograms for the galactic globulars show the expected sharp maximum at about $+0.52$, with a spread from $+0.40$ to $+0.70$ for the alternative of a small variation in intrinsic color with spectral type. For the alternative of a larger intrinsic variation, there is a color range from about 0.45 to 0.90, with a broad main maximum near 0.55 and a secondary one close to 0.75, but the latter is largely due to the assumed late spectral type for the group of center clusters. The histogram for M31, on the other hand, shows no clear-cut maximum in the range from $+0.50$ to $+0.90$. Instead, the M31 color data show some slight indication of three maxima at about $+0.57$, $+0.70$ and $+0.82$, but the bias toward the brightest clusters, and the possibility of a small amount of reddening for a majority of the clusters seen over the spiral, make the reality of the maxima very questionable. Unless the corrections for space reddening in the spiral are considerable, however, it seems probable that the M31 globulars may be systematically redder than those in the Galaxy, by an amount up to 0.2 mag.

When the cluster magnitudes are summed in 0.5 mag. intervals, the histogram of the apparent V -magnitudes for the M31 clusters shows a well-defined maximum in the interval 15.5 to 16.0, while that for the absolute magnitudes of the galactic globulars has a somewhat broader maximum in the interval -7.5 to -8.5 . The peak for the M31 clusters, however, could be largely due to observational selection, since the fainter clusters are so poorly represented in the sample. Thus, for a distance estimation of M31, instead of using mean magnitudes, it seemed better to try to match the high-luminosity parts of the frequency distributions. Although this procedure also is attended with considerable uncertainty, these data indicate an apparent modulus in the range from 23.5 to 24.0. This estimate depends on the assumptions of $M_p = 0.0$ for the cluster-type variables in the galactic globulars, and of negligible galactic absorption toward M31. It may be significant that, for an M31 modulus of 24.6 (Sandage 1958), there are 10 clusters in M31 with luminosities higher than $M_V = -10$, whereas in the Galaxy none of the globulars observed on this program have a luminosity higher than $M_V = -9.6$. These results from comparison of luminosity frequencies, when taken together with those for the colors, give some support to the possibility that the globular clusters in M31 and in the Galaxy may be systematically different.

When the galactic globular cluster angular diameters containing 0.9 the total light are converted to linear diameters by use of the absorption-corrected distances, it is found that the diameters are nearly independent of luminosity in the luminosity range from $M_V = -6.8$ to -9.6 , and in the diameter range from about 20 to 50 parsecs. Subdivision of the data into three groups with $b > 20^\circ$, $-20^\circ < b < +20^\circ$, and 10 clusters in the galactic center direction gives mean diameters of 34, 28, and 22 parsecs, respectively; but the trend downwards may be mainly the result of increasing field star density. On the other hand, there is the necessarily accompanying marked correlation of mean absolute surface

brightness with luminosity, with the brightest clusters having mean surface luminosities 3 mag. brighter than the faintest.

The distance to the galactic center has also been re-estimated with these new data, first, from all clusters whose distance moduli depend only on cluster-type variables and, in a few cases upon brightest stars. For the same three groups used in the diameter discussion, outlying, intermediate, and central, the group mean absolute visual total magnitudes are -8.2 , -8.1 , and -8.3 , respectively, for 45 of the best-observed clusters. Moreover, the spread in luminosity in each group is nearly the same, even for the group of 10 center clusters for which photometric distance moduli are available. This last circumstance suggests that the grand mean of -8.2 may also be representative of the much larger group of 22 center clusters for which total apparent V -magnitudes corrected for absorption are available. This mean is 7.5 or 7.1, depending upon the two ways used to estimate color excess, so that $m - M = 15.7$ or 15.3. If the centroid of this group is the galactic center, the distance is 13.8 or 11.5 kpc. Second, if we use our color excess for NGC 6522, $E_{(P-V)} = 0.48$, and Baade's (1953) apparent modulus for the cluster-type variables in the same field, $m - M = 17.3$ (for $M_p = 0$), and correct the latter for photographic absorption by $4 \times 0.48 = 1.9$ mag., we obtain $(m - M)_{\text{corr.}} = 15.4$. These estimates of the modulus agree fortuitously too well, but the corresponding mean distance of 12.4 kpc is 50% larger than Baade's value of 8.2 kpc. The comparison is an indication of how uncertain distance estimates can be when they depend on evaluation of color excess and absorption of objects in the region of the galactic center.

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DISCUSSION OF KRON AND MAYALL'S PAPER

YOUNG: Is it true that if you make the RR Lyrae stars $\frac{1}{2}$ to 1 magnitude fainter, then the distance to the galactic center is brought back to a more reasonable value?

MAYALL: That is correct.

SMITH: In regard to the point of making the RR Lyrae stars fainter, do members of this symposium have any remarks on Pavlovskaya's paper of 1953, in which she computed statistical parallaxes of this group more thoroughly than anyone else. She found $M_v \approx +0.5$. Do you have any faith in this work?

MAYALL: Since Kron and I were not directly concerned with the absolute magnitudes of the RR Lyrae stars, perhaps Arp would like to consider that question.

ARP: I cannot say how accurate her determination was. Some people have voiced the opinion that the method is intrinsically inaccurate and others believe that under certain conditions it will work.

McVITTIE: Wasn't Vyssotsky of the opinion at the Charlottesville conference on the Cosmic Distance Scale that there was some intrinsic uncertainty in her method? I seem to remember reading it in the report.

SANDAGE: It has always appeared to me that the method will work *only* if you are dealing with a homogeneous group. But the fact that the kinematic properties of the RR Lyrae stars in the field have been shown to define a completely inhomogeneous group (by Preston, Kinman, and others) means that the solar motion with respect to the RR Lyrae's is different for each "sub-group." Therefore, if you throw *all* of these variables into a bushel basket, you will get out a mean value for M_v —but this mean has no reality, even though the proper motions may be extremely good.

DE VAUCOULEURS: I would like to suggest to Dr. Mayall that possibly using the diameters at half-total luminosity would give you more stable diameters than at $0.9 L$.

MAYALL: This is possible and should be looked at.

DE VAUCOULEURS: You can change the total magnitude quite a bit, but the half-luminosity diameters are quite stable.

SANDAGE: Perhaps at this point Dr. Hiltner would like to comment on his recent observations of the clusters in M31 and M33.

HILTNER: Well, it just so happens that I have a couple of slides here. (Laughter.) These

observations were taken because I was interested in getting polarization measurements to establish the existence or non-existence of a magnetic field in M31 and M33. The diagram shows the $U-B$, $B-V$ plot for the clusters in M31 and in M33. The scatter of the observational points is probably real, i.e., not due to reddening, because the blue clusters are spectroscopically of earlier type than the redder clusters. So here we see the intrinsic differences among the clusters themselves. Furthermore, the clusters in M33 are in general bluer than the clusters in M31. They are also about 2 magnitudes fainter than those in M31.

MAYALL: I should like to mention that our results for four clusters in M33 are entirely consistent with what Hiltner has just said. Their colors on the $P-V$, $V-I$ system place them in the blue group on one of the slides of the globular clusters in M31. Two of them were close to zero in color index, and their magnitudes are fainter than those in M31. The brightest one is almost 2 magnitudes fainter, so there are different breeds of clusters in these two galaxies.

SANDAGE: Would you think that these clusters in M33 might be young open clusters like the Pleiades in our own Galaxy if it were more populous?

MAYALL: Yes, that is possible.

SANDAGE: From your observations and Hiltner's observations, would it be correct to say that we don't know any true globular clusters in M33?

MAYALL: We've only observed four. They were the four brightest ones for which we had charts; three were marked many years ago by Hubble, and one was more recently marked by you.

HILTNER: I should have pointed out that there are a few clusters in M33 which fall in the same general region of the $U-B$, $B-V$ diagram as the clusters in the Galaxy and in M31. Of the 23 clusters I observed in M33, there were 5 in this region which could well be globular clusters of the normal type but they are fainter than those in M31.

KRAFT: The colors of these M33 clusters are to some extent very much like the Pleiades. If you accept the integrated apparent magnitude as given, for example, in the Alter cluster catalogue, then you come out too faint if you interpret these as galactic clusters. You would have to add a richness factor of about 3 or so.

THE INTEGRATED SPECTRA OF GLOBULAR CLUSTERS

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Introduction. The present discussion will be concerned exclusively with spectroscopic characteristics of a representative sample of the integrated light of certain globular clusters; a short summary of the published results on spectra of individual stars in globular clusters is included as an appendix.

In a classical paper Mayall (1946) established for the first time the great range in spectroscopic characteristics of the globular clusters; he reviewed the earlier Harvard (Cannon 1929) classifications for many of the clusters, and demonstrated their unsuitability for modern purposes, because of the fact that the distribution of energy in the continuous spectrum had been used as one criterion of classification. In addition to reddening effects in the Harvard spectral types, there are also wide differences in some cases between the objective prism and slit spectrographic results. For example, the Harvard spectral type of NGC 6341 (M92) is G5?, while both Lick and McDonald spectrograms give types of late A or early F. These comments should not be interpreted as criticisms of the Harvard classification; it is obvious that great difficulty would be encountered in classifying objective prism spectra of such sources.

The illustrations accompanying Mayall's paper show clearly the great differences which exist in the violet region of the spectrum between clusters such as NGC 6341 and NGC 6356; if these differences are expressed in terms of spectral type, the range is greater than a full spectral class.

Mayall's paper contains two basic discoveries in the field of spectroscopic phenomena: he noted that the weakness of certain lines in his globular cluster spectra bore similarities to the weak-lined characteristics in the spectra of several high-velocity stars and of the cluster-type variable RR Lyrae; he also noted the presence of a fairly compact group of about ten clusters centered at ($l = 330^\circ$, $b = -10^\circ$), for which the average spectral type was found to be later than that for the system of globular clusters as a whole.

Ten years later, Morgan (1956) published a rediscussion of the integrated spectroscopic characteristics from additional plates of higher dis-

persion obtained at the McDonald Observatory combined with Mayall's spectrograms. In this investigation, a dependence of degree of metallic line weakening on distance from the galactic nuclear region was found: a group of eight clusters located in the direction of the galactic nucleus, together with two others near the galactic plane, were found to have metallic-line intensities considerably greater than clusters situated in high latitude. It was later suggested in a private communication by Baade that the significant correlation is probably with distance from the galactic plane, rather than from the nucleus itself.

The present paper is based on a rediscussion of the earlier spectrograms, together with spectra of a number of additional globular clusters taken with the 82-inch Cassegrain spectrograph at the McDonald Observatory. The new spectrograms were obtained for the purpose of investigating further the relationship between metallic-line intensity and position of clusters with respect to the Galactic plane and Galactic nucleus.

The general interpretation of composite spectra. The problem of the interpretation of highly composite spectra is difficult, even under the most favorable circumstances. In cases where stars of high metallic content only are concerned, similarities to the "normal" distribution in certain critical regions of the HR diagram have to be assumed in order to derive results which can be considered even approximately unique. For example, a composite spectrum which shows features pertaining to stars of both early and late spectral type allows of a variety of interpretations, depending upon whether the later-type stars are "normal" giants (G8III and later), or are giants of the type observed by Arp in the region of the Hertzsprung gap in two non-cluster fields of the Small Magellanic Cloud. When the possibility of the contribution of stars of varying degrees of metallic-line weakening to the integrated luminosity of a composite system are considered, a further major complication is introduced into the analysis of composite spectra. In addition to these kinds of uncertainty, there are also the complications in the discussion of multi-color photometric observations of composite sources, caused by ultraviolet excesses of weak

ned stars, and the effects of interstellar reddening and emission lines in the case of galaxies.

The above-mentioned ambiguities are inherent and do not seem likely to be resolvable simply by applying quantitative methods to the analysis of composite spectra. The total result of these ambiguities is to limit the accuracy with which astrophysical spectral classification can be carried out in practice, either by visual or spectrophotometric methods.

Except, then, in the case of certain favorable situations, determinations of spectral type or practical attempts to derive luminosity functions tend to take on a certain artificial or formal character, due to possible non-uniqueness of the resulting interpretation. The most determinate cases are:

(1) The blue-violet spectrum gives evidence of being of early type, together with emission lines of [O III], [O II] and H. Here, the presence of outstanding numbers of stars earlier than class F can be deduced; however, some ambiguity would probably remain with regard to the abundance of metals in such systems. Examples: the irregular galaxies NGC 4214 and NGC 4449.

(2) The spectrum as a whole, over a considerable range in wave length, resembles closely a blending of spectra of strong-lined, yellow-red giants. In this case, it seems probable that the greater part of the contribution to the total luminosity comes from strong-lined stars of classes B8-M. This is the situation encountered in the case of the bright elliptical galaxies in the Virgo cluster, and the nuclear regions of spirals like M31.

(3) Extreme "weak-lined" spectra. Here, the composite spectrum bears a close resemblance to that of individual F-type stars of the extreme weak-lined category. The determination of the distribution of luminosity among stars of differing temperature and absolute magnitude in such a composite source is probably not possible from the spectroscopic evidence alone; however, the determination of the weak-lined nature of the component stars seems definite. Examples: the globular clusters M92 and M15.

In the case of spectra which do not fall into one of the three above-mentioned categories, the determination of spectral types takes on a somewhat formalized nature. The appearance of an integrated spectrum at a certain wave length can be described in terms of blends of two, three or more spectra artificially superposed; that is, the astrophysical implications of such composite

spectra are to a considerable extent held in abeyance.

The significance of a general spectral classification of composite sources is therefore a most important question. We have, near the two extremes of the observed spectral range, relatively definite indications of certain physical situations: galaxies of spectral types B and A possess relatively large numbers of early-type stars, together with a high density of gas; at the other extreme, the strong-lined, giant K-type spectra observed seem rather definitely interpretable in terms of large relative numbers of yellow giant stars.

For intermediate integrated spectral types, intermediate situations with regard to the stellar population may be inferred; however, the determinateness of the physical situation for these intermediate spectra is considerably less than in the cases of the two extremes.

The spectral classification of globular clusters. The spectral classification of the integrated light of globular clusters has special characteristics which distinguish the process from that of the classification of galaxies. The earliest types assigned from the McDonald spectrograms are early F; and when spectra of sufficiently high dispersion are available, these early-type globulars invariably are found to have extremely weak metallic lines. On passing toward globular clusters of successively later spectral type, the metallic absorptions tend to approach the intensities of strong-lined objects. In the case of clusters similar to NGC 6356, the metallic absorptions in the ultraviolet region resemble approximately those in strong-lined G-K spectra; however, a more precise recent comparison shows that even in the case of NGC 6356 the metallic absorptions in the blue and green regions are somewhat weakened.

As a result of the increase in the number of globular clusters observed, several have been found which simulate even more closely the spectrum of strong-lined stars. In particular, the two clusters NGC 6528 and 6553 have considerably stronger metallic-line absorption in the blue and green regions than does NGC 6356; these two clusters of latest type seem to have populations remarkably similar to that of a region in M31 approximately 200 parsecs in projected distance from the nucleus, as far as the evidence in the spectral region $\lambda\lambda$ 4300-4800 is concerned. The spectra of these two clusters also resemble closely those of two non-cluster regions in the Great Star

Cloud in Sagittarius near the region of the Galactic nucleus, in the blue-green region.

A reclassification of the globular cluster spectra of highest quality has been carried out from the point of view of metallic-line intensity. Instead of expressing the reclassification in terms of spectral types, the clusters have been assigned to one of eight metallic-line groups. In Group I are the extreme weak-lined clusters NGC 6341 and NGC 7078; in Group VIII are the two strong-lined clusters just described: NGC 6528 and NGC 6553. The criteria for assignment to the groups are the intensities of: the G band, the arc metallic lines in the blue-green region, and the difference in intensity of the continuous spectrum on the two sides of $H\gamma$. The classification by groups is given in Table I.

TABLE I. CLASSIFICATION OF INTEGRATED SPECTRA OF GLOBULAR CLUSTERS BY GROUPS

Group	Members
I	6341, 7078
II	5024, 5139, 5272, 5904, 6656, 6981, 7006, 7089
III	6205, 6229, 6642, 6715, 6809
IV	6254, 6273, 6402, 6522
V	6712
VI	6356, 6760, 6838
VII	6440, 6637
VIII	6528, 6553

The present group classification is not intended to supersede the spectral types of the earlier paper (Morgan 1956); it expresses the peculiarities of the integrated spectra in a somewhat different manner, and adds a new category of strong-lined globulars (NGC 6528 and NGC 6553). The criterion of the strength of the metallic-line blends in the blue-green region makes possible the use of spectrograms of considerably lower dispersion than could be used with precision earlier: this, in turn, makes possible direct comparison of metallic-line strength in globular clusters with the nuclear region of our Galaxy, and with large numbers of integrated extragalactic sources.

The globular clusters spectroscopically assigned to the nucleus-disk system. A total of 13 globular clusters can now be assigned to the flattened nucleus-disk system by the lateness of their spectral types (and therefore by the greater intensity of their metallic lines). The clusters are listed in Table II and their positions plotted in Figure 1; the galactic coordinates are taken from Shapley's *Star Clusters*.

The last three clusters in the table may be considered members of the Galactic disk system.

TABLE II. NUCLEUS-DISK GLOBULAR CLUSTERS

NGC	l	b
6304	323°	+ 5°
6356	334	+ 9
6440	335	+ 2
6441	321	- 6.5
6528	328.5	- 5
6553	332.5	- 5
6624	330	- 10
6637	329	- 11
6638	335.5	- 7.5
6652	328.5	- 13
6712	353.5	- 6
6760	3	- 5
6838	24.5	- 5.8

It should be emphasized that the metallic-line strength is not identical in all of the clusters in Table II; however, all thirteen have the characteristic of later spectral types than any others observed at McDonald. It is obviously of the greatest importance to extend integrated spectroscopic observations to the globular clusters observable only in the Southern Hemisphere when such observations—with radial velocities—are available, a comparison of the kinematical properties of the nucleus-disk globulars with those of the galactic halo can be made.

The integrated population characteristics of the nuclear region of the galaxy. A series of spectrograms was obtained of various regions in the Great Star Cloud in Sagittarius with the 82-inch McDonald spectrograph; these spectrograms are identical in dispersion and slit width with those used to classify the strong-lined globular clusters and the integrated properties of galaxies. The new spectrograms indicate that in the spectral interval $\lambda\lambda$ 4300–4800 the principal contributors to the luminosity of the Galactic nuclear bulge within angular distances of approximately 5°

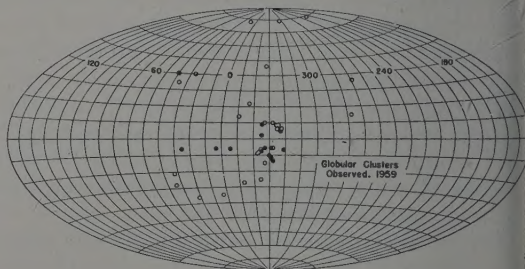


Figure 1. Globular clusters whose integrated spectra show weaker (open circles) and stronger (solid circles) metallic lines. There is a considerable range in the metallic line intensities among different clusters in each category. The two clusters having the strongest metallic lines are the two filled circles closest to the position of the galactic nucleus ($l = 328^\circ$; $b = -1\frac{1}{2}^\circ$); these clusters are NGC 6528 and NGC 6553.

from the nucleus itself, are probably K stars; the spectra of the most transparent regions, in this wave length range, resemble the spectrum of M31 near its nucleus.

This effect is most clearly shown in the transparent area in the immediate neighborhood of NGC 6522; in other regions of the Great Star Cloud in Sagittarius, where increasing amounts of interstellar absorption are observed on direct photographs, the spectrograms show a progressive effect of increasing contribution from stars of earlier type. This can be interpreted in terms of a population change on passing outward radially from the nuclear bulge.

Such an effect shows clearly on spectrograms taken of M31 by H. W. Babcock at the Lick Observatory some years ago, Babcock's spectra were obtained with the Mayall nebular spectrograph in conjunction with a small image-forming mirror which allowed the registration of M31 to a considerable distance from its nuclear bulge. The enhancement in intensity of the *H* lines indicates that the disk population at considerable distances from the nucleus of M31 differs systematically from the nuclear bulge itself. (This conclusion revises and corrects earlier statements by the writer, e.g., see *Stellar Populations*, Conference Sponsored by the Pontifical Academy of Science and The Vatican Observatory, p. 326, 1958, and elsewhere. The difference in spectroscopic characteristics between the nuclear bulge of centrally-condensed spirals and the outer disk-arm region is probably a general phenomenon; further investigation will be necessary to determine whether there are detectable spectroscopic differences in the absorption spectra of nuclear and outer regions of spirals having a minor degree of central concentration of luminosity.)

Now, if a similar situation exists in our galaxy, it would be expected that absorbing clouds in the line of sight toward the nucleus would tend to cut down or hide the contribution of the latter to the integrated spectrum; the observed spectra, then, would tend to refer to stars of the galactic disk and arms, and a correspondingly earlier spectral type would result. The observational difficulties in partially obscured regions are of course greater, since the surface brightness is lower and disturbances from the night sky spectrum are more serious.

The spectrographic results of Humason (Baade 1958) can be explained in terms of the greater area of sky recorded on his spectrograms than for the McDonald spectra; in the latter case, the

projected slit length was 2', and the 82-inch mirror was used to form the image of the sky. Since Humason's spectrum of the Great Star Cloud described by Baade integrated over a solid angle of 4.2 degrees, the contribution to the light in the case of his spectrogram included regions of varying degrees of obscuration. It appears that only in the small, most transparent regions is it possible to obtain clear evidence of the integrated population of the galactic nucleus in ordinary photographic wave lengths.

Conclusion. Observation of the integrated spectrum of additional globular clusters has resulted in the discovery of two clusters (NGC 6528 and NGC 6553) possessing even stronger metallic-line absorptions than any noted earlier. These clusters are located at relatively small projected distances from the galactic nucleus (4° and 6°, respectively), and resemble the nuclear region in spectroscopic characteristics in the wave length range $\lambda\lambda$ 4300–4800. The two clusters appear to be of considerable interest as representing a possible intermediate stage between the halo globulars and open clusters; in particular, a detailed comparison of their color-magnitude diagrams with that of M67 would be of interest. Because of the spectroscopic similarity of NGC 6528 and NGC 6553 to the region of the Galactic nucleus, it would also be of interest to survey these clusters for possible distance indicators, since it seems possible that they may be located within a relatively small distance of the Galactic nucleus itself.

Acknowledgment. I am greatly indebted to Dr. N. U. Mayall for permission to examine Babcock's Lick spectra of M31.

APPENDIX

An historical summary of the observations of individual spectra in globular clusters is given in "Star Clusters," by Helen Sawyer Hogg (1959); the most important published work of the past ten years is summarized here.

The establishment of the extreme weakness of the metallic lines in the spectra of red giants in M92 is due to Baum (1952); the latter deduced spectral types of class F for ten red giant stars in this cluster, and pointed out the large discrepancy between color and spectral type.

Deutsch (1953) resolved this discrepancy at a symposium held in Paris in 1953. He showed that if the spectral types are determined from the ratios of certain metallic lines, types result that are only slightly earlier than the observed

colors; that is, the giants in M92 are to be considered basically as K stars—both from the point of view of color and spectrum. An astrophysical investigation by Greenstein (1953–1954) of bright K giants in M92 and M13 gave clear evidence that the excitation temperatures are lower than previous estimates based on spectral classification alone; some low-level lines bore similarity to those in an early M star. Blue stars of the horizontal branches of the globular clusters M3 and M13 were observed by Münch (1953–1954); they were found to be recognizably different from ordinary blue stars. The variation of metallicity intensity from cluster to cluster was emphasized by Deutsch (1953–1954). Investigation of high-dispersion spectrograms of the brightest stars in M13 by Greenstein (1956–1957) showed

that the spectra of these stars resemble those of high-velocity stars in the solar neighborhood.

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DISCUSSION OF MORGAN'S PAPER

SANDAGE: Morgan's result revises much of the speculation about population types—especially revises the identification of the population of the nucleus of M31 with any and every globular cluster you would like to pick in our own galaxy. This identification can now be made with much higher precision, and gives new information about the chemical composition of the center of M31.

McVITTIE: Is enough known in the Magellanic Clouds to make this kind of subdivision?

MORGAN: I do not have any direct information. Can Sandage comment?

SANDAGE: There seems to be a division in the types of color-magnitude diagrams for clusters near to the centers of the LMC and SMC and the outskirts. (*Editor's note:* This is brought out in the section entitled General Discussion.)

DE VAUCOULEURS: Could Dr. Morgan comment on the comparative characteristics of

the *UBV* colors of the inner part of M31 and of globular clusters? For the former we have, approximately, $B - V = +0.9$, $U - B = +0.6$. In the case of the unreddened globular clusters, the *UBV* photometry seems difficult to reconcile with that for M31.

MORGAN: The unreddened globular clusters tend to be of the halo type; the disk globulars, which have spectra more nearly resembling that of the nuclear region of M31, are more or less reddened. Harold Johnson has published *UBV* photometry for one of the disk globulars of latest spectral type—NGC 6553. The spectrum of the latter resembles that of the nuclear region of M31 in the spectral range $\lambda\lambda$ 4300–4800. Johnson's photometry for NGC 6553, when compared with that of de Vaucouleurs for M31, gives a quite consistent result on the assumption of similar stellar populations and a reddening line of normal slope.

COMPARISON OF GLOBULAR CLUSTERS IN THE GALAXY AND IN THE MAGELLANIC CLOUDS

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Since the earliest days of operation of the 74-inch Radcliffe reflector, the globular clusters in Large and Small Clouds have received considerable attention. The programs have been devoted to both direct photography and spectroscopy.

In direct photography, efforts have been concentrated on the discovery of variables, particularly those of RR Lyrae class. But as a preliminary to a search for variables in any particular cluster, pairs of direct photographs in two colors have usually been taken to determine whether or not the brightest stars are red.

Despite some doubts which have been expressed whether the Magellanic Clouds do possess any globular clusters like those in our own Galaxy, there can be no doubt now that both Large and Small Clouds do in fact contain ordinary globulars, as judged by the colors of their brightest stars and by their containing RR Lyrae and other variables. We proceed to consider various individual globulars in turn.

NGC 121 (SMC). The brightest stars are red. Information about the 3 known RR Lyr variables in this cluster has already been published (Thackeray 1958). Their characteristics are in accordance with normal behavior of RR Lyr variables in ordinary globular clusters.

The other two variables in NGC 121, both very red, have periods greater than 100 days and are among the brightest stars in the cluster.

Kinman has important new spectroscopic data on NGC 121. From two Radcliffe spectra (380 Å/mm) he finds a *CH/H* classification of F7–F8. From these two same spectra he measures the radial velocity as $+86 \pm 20$ km/sec. This is quite consistent with membership in the Small Cloud, although the radial velocity of this far outlying portion of the Cloud is not yet well determined.

NGC 1978. This is a spectacular, elongated globular in the Large Cloud, the first instance found at the Radcliffe Observatory to have its brightest stars red (Thackeray 1951). The cluster is shown in Figure 1, which is reproduced from a 103aO plate with no filter, taken with the 74-inch reflector exposed for 30 minutes.

Wesselink has found four variables in the region of the cluster; one is a red long-period, while the two others have RR Lyr characteristics. The field is a very crowded one and consequently the cluster is not very well suited to photometry.

NGC 1783 L 1835. These also appear to be ordinary globulars with brightest stars red whose membership in the Large Cloud cannot be doubted. They lie in dense regions and are therefore unsuited to searches for variables.

NGC 1835 deserves special mention because Kinman has obtained two Radcliffe spectra at 86 Å/mm which he classifies as follows:

From <i>H</i> lines	F6
<i>Fe</i> lines	F3
<i>CH/H</i>	intermediate

This trend for the three criteria is quite typical of ordinary globulars. The measured radial velocity of NGC 1835 is $+188$ km/sec, slightly smaller than this part of the Large Cloud, but no weight can be attached to the discrepancy

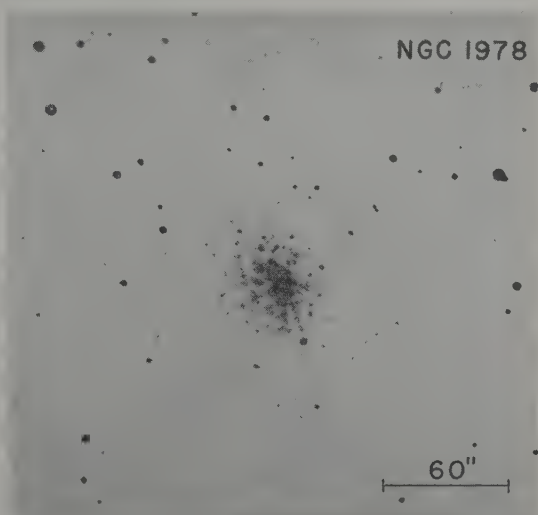


Figure 1. NGC 1978 in LMC. Reproduction is from a Radcliffe 74-inch 103aO plate exposed for 30 minutes with no filter.

until more is known about the velocity dispersion of the Cloud globulars.

NGC 1466. This globular, with brightest stars red, lies roughly midway between the two Clouds close to the boundary of hydrogen 21-cm isophotes of the Large Cloud. There is no reason to doubt its Cloud membership, more especially as the magnitudes of the bright stars and of the variables found agree with those of other Cloud globulars. The cluster is shown in Figure 2, which is reproduced from a 103aO plate with no filter, taken with the 74-inch reflector exposed for 30 minutes.

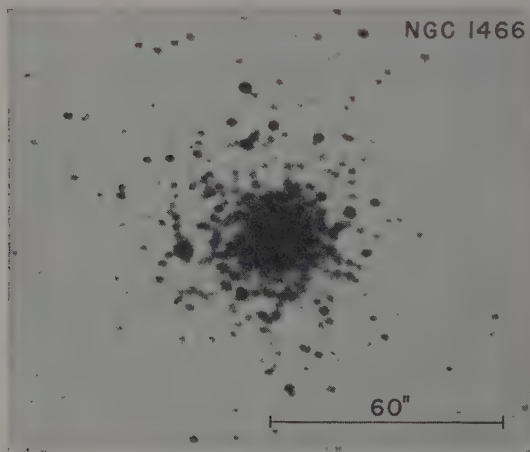


Figure 2. NGC 1466 between the LMC and the SMC. From a 74-inch 103aO plate exposed for 30 minutes with no filter.

Wesselink has been highly successful in the discovery of variables, mostly of short period, in this cluster; the total discovered now amount to 44. He has found periods for seven, 6 of which are Bailey a types with periods ranging from 0.493 to 0.590 day. The seventh is of c-type and Wesselink's period is 0.358 day, although he has proof from observations on consecutive nights that the variable does not repeat itself exactly; the amplitude must be varying, a not uncommon feature of RR Lyr variables.

NGC 2257. This is another outlying globular to the Large Cloud. Its brightest stars are red and like NGC 1466 it is rich in RR Lyr variables. Alexander has discovered 17 certain and a further 8 doubtful variables in this cluster. He has found certain periods for four, ranging between 0.5056 and 0.5468 day. A fifth variable has been proved to be of c-type, but the data do not distinguish

certainly between a period near $\frac{1}{4}$ and one near $\frac{1}{3}$ day.

These two c-type variables (in NGC 1466 and 2257) are the first discovered in either Cloud.

Figure 3 shows the frequency distribution of the periods found at the Radcliffe Observatory combined in one histogram. The mean period for the 13 known Bailey a b variables is 0.548 day. The peak in periods around 0.50 to 0.55 day and the absence of periods 0.40 to 0.45 day are striking features. This seems to indicate that the Cloud globulars tend to form a group analogous to those in the Galaxy which include M3, etc., but not ω Centauri. However, further researches in the Clouds might of course change the form of the histogram completely. It cannot be stressed too strongly that the derivation of the correct period for even one of these faint variables is a matter of some difficulty; the seeing has to remain of first class quality for long periods of several consecutive nights, and while such conditions frequently obtain in the Transvaal winter, unfortunately they do not do so in the Magellanic Cloud season.

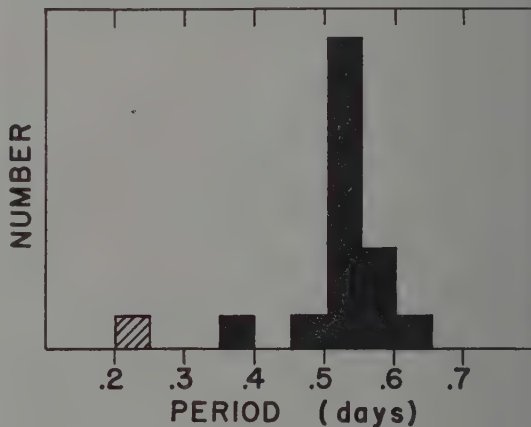


Figure 3. The frequency distribution of known periods of RR Lyrae variables in the Magellanic Clouds.

Spectra of Cloud Globulars. As is well known, Miss Cannon classified a number of cluster spectra—apparently globular in form on direct photographs—as A type. Spectra of such clusters were obtained in early days at the Radcliffe Observatory with a Newtonian spectrograph, and a number of velocities have been measured. It is hoped that progress will be made in this program in the near future; in particular, that more spectra of ordinary red globulars will be obtained. We

would very much like to know whether the velocity dispersions of these ordinary red globulars and of those of earlier type are the same, or not. In the meantime, progress has been made with measurement of stellar velocities, and it is essential to know such velocities and the law of rotation for the Large Cloud before we can begin to study accurately velocity dispersions of any subsystems within the Cloud.

The prototype of the early-type globulars is NGC 1866, which, as is well known, contains a considerable number of 3-day Cepheids. Arp and Sandage are studying 2-color light curves of these Cepheids on the basis of the Radcliffe material, together with material they obtained in their respective visits to Radcliffe. These giant clusters certainly appear to be globular in form, but are rich in bright blue stars; NGC 1866 and some others also have many bright red stars. It is possible that clusters like M11 form counterparts in our own Galaxy.

47 Tucanae. Two Harvard variables (810, 814) discovered by Miss Leavitt many years ago have been regarded as too bright to be members of 47 Tucanae. However, it was pointed out at the Rome Semaine (1957) that the distance of 47 Tucanae has probably been overestimated, and the question of the membership of the two variables has therefore been reexamined at the Radcliffe Observatory. Mrs. Nail recognized that the periods were short, but seemed to think that they might be W UMa foreground variables.

Radcliffe observations (Feast, Thackeray and Wesselink 1960) have established both variables as of RR Lyr type. HV 810 has period 0.73652 day with a rise to maximum lasting one-tenth of a period, and is thus of Bailey class a. HV 814 is a Bailey c-type with period 0.37143 day and a sinusoidal light-curve. Wesselink's photoelectrically observed mean color ($+0.27$ corrected to $+0.22$ for interstellar reddening) lies within the normal range for c-type variables, and definitely rules out the possibility of a W UMa variable.

We therefore have two RR Lyr variables (mean = 13.9) within the radius of 26.8 minutes of arc of the cluster center (HV 810 is as close as 2.2 minutes of arc of the center). From the quoted densities of field RR Lyr variables, we find a chance of 50 : 1 against HV 810, 814 being foreground RR Lyr variables.

Two spectra of HV 810 and one of 814 have been obtained, all long-exposure covering an ap-

preciable fraction of the period. Both agree within the observational error with the radial velocity of 47 Tucanae, after making a slight correction appropriate to phase. The chance of finding a field Population II object in the direction of 47 Tucanae with its small radial velocity is small—about 0.08. The chance of finding two such objects is therefore 150 : 1 against.

Combining these two arguments, we find that the chance that both HV 810 and 814 are not members of 47 Tucanae is of the order 1/7500. This assessment takes no account of the observation that the two variables have the same median apparent magnitude (13.9 visual). We regard the membership of these two variables as a fact established with far greater certainty—by several orders of magnitude—than many astrophysical opinions held widely in the mid-twentieth century.

The spectral classes found for these two variables are both later by half a type, if judged by the hydrogen lines rather than the metals. This is in accordance with the normal behavior of RR Lyr variables. It is of interest, however, that the periods are long for their respective Bailey classes. *Spectral Types of Individual Stars in 47 Tucanae* (Feast and Thackeray 1960). Altogether we have 67 spectra of 34 stars in 47 Tucanae, many of them taken at 49 Å/mm.

Among 23 giants, not known to vary in light, we find 5 G-types, 11 K-types, and 7 M-types. The M-types were classified by the TiO bands. Such stars are unknown in other globulars in the Galaxy.

These giants are spectroscopically much closer to "normal Population I" giants, the metal/*H* and metal/metal criteria giving essentially the same spectral types. There is, however, some weakening of *CN*, a well-known characteristic of globulars and high-velocity objects, but the *CN* weakening in 47 Tucanae is near the limit of detection. The integrated spectrum of 47 Tucanae has been classified by Kinman as G3 whether *CH/H*, *H*, or *Fe* are used as criteria. This is further evidence that 47 Tucanae does not show extreme metal weakening.

From the velocities of these stars, measured independently by two observers, an uncorrected velocity dispersion of 8.3 ± 1.3 km/sec is found, which is reduced to 6.3 km/sec or less when allowance is made for observational error. A generous upper limit to the mass of 47 Tuc of $5 \cdot 10^6$ solar masses is set by these observations.

The late-type variables have also been studied spectroscopically on many occasions. The three regular variables have stronger TiO bands than any of the other M stars; their absolute magnitudes at maximum (visual) are -4.1 or -3.6 according to whether the RR Lyr variables are assigned absolute magnitudes 0.0 or $+0.5$; corresponding values for the three irregular or semi-regular variables (numbers 5, 7, and 8) are -2.6 and -2.1 .

The three regular variables are such conspicuous members of the cluster at maximum that it is unlikely that such objects have been missed in any of the familiar globular clusters in the Galaxy. However, one may ask the question whether 47 Tucanae is not an unusually young globular cluster, by galactic standards, and whether similarly bright variables might not perhaps be found in some Large Magellanic Cloud globulars. The two red variables in NGC 121 may be counterparts in the Small Cloud.

Finally, there is the question of the blue star in 47 Tucanae, easily the brightest star photographically in the whole cluster. This star is identified in Figure 4, which is reproduced from a 2-minute 103aO plate of the center of 47 Tuca-

nae taken with the 74-inch reflector. Its spectral type is B8 III. Isolated bright blue stars are known in other globulars. Such stars, which are not explained in terms of modern ideas of stellar evolution—unless they represent stars born late in a cluster's history—deserve further attention. Kinman has observed a bright star of type A5–A7 (luminosity class III or brighter) in the cluster NGC 6752, with the same radial velocity; membership seems probable but has not yet been proved with certainty.

Other Southern Globulars. Kinman has recently completed a fine program on the spectra of southern globulars which rounds off Mayall's northern work. With a dispersion of $86 \text{ \AA/mm}$ used almost throughout, the quality of Kinman's velocities and spectra is high. The program included 16 southern clusters for which no velocities or types were hitherto known.

From the radial velocities of 70 clusters, Kinman finds a solar motion of $167 \pm 30 \text{ km/s}$, without any clear evidence of differential motion in the cluster system. He finds that field RR Lyr variables of the same period range as those occurring in globular clusters have the same kinematic properties as the system of clusters; he suggests that these stars and the clusters have the same origin.

Kinman finds a correlation between the integrated spectral type of a globular cluster and its concentration to the galactic plane. Clusters of the earliest types with marked signs of metal weakening form an extended spherical distribution; those of later types with more normal metal intensities are strongly concentrated to the plane. He has computed the effects of varying metal/ H abundance, and finds that even with a value as low as one-tenth the solar value, the spectra of giants will show little effects of metal weakening; but the effects should be much more marked for the subgiants. Among the clusters he has observed, variations in metal/ H ratio seem to range from one-tenth to less than one-hundredth the solar value.

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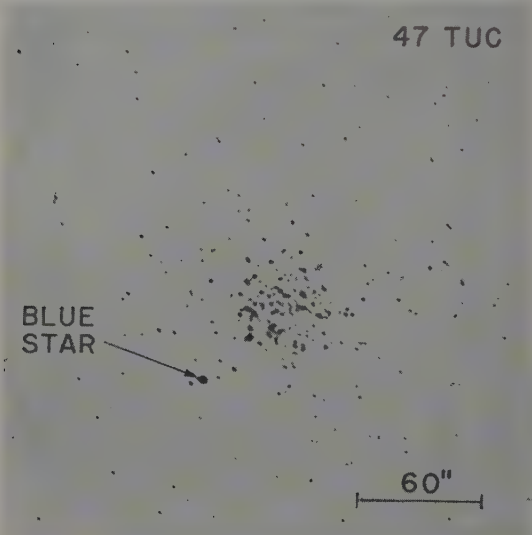


Figure 4. A 2-minute exposure of 47 Tuc taken with the 74-inch telescope on a 103aO plate with no filter. The position of the B8III blue star is shown.

DISCUSSION OF THACKERAY'S PAPER

Editor's Note: Dr. Thackeray was not present at the symposium, but his paper was read in absentia. The following comment, which does not appear in the printed text, was made by Sandage during his reading of the text.

"The appearance of TiO bands in the spectra of the giant stars in 47 Tucanae would seem to be highly significant. As Thackeray points out, 47 Tucanae is the only known globular cluster with genuine M stars. The explanation might follow from the fact that 47 Tucanae has a higher metal abundance than any of the well studied halo clusters in the galaxy. Since the abundance of TiO goes as the square of the metal

content, the low-metal halo clusters might not be expected to have TiO even though the temperatures of the reddest stars on the giant branch are certainly low enough. Thus, the presence or absence of TiO in the red giant stars in globular clusters may be a powerful and simple abundance indicator. This speculation can be checked by looking for TiO bands in the individual stars of NGC 6553, NGC 6356, and other members of Morgan's strong-line group of clusters near the galactic nucleus."

Comments on the "normality" of some of the clusters discussed by Thackeray (such as NGC 121, 1466, 1783, 1978, and 2257) are given in the General Discussion of this symposium.

 THE ABSOLUTE MAGNITUDES, COLORS, AND METAL ABUNDANCE
OF STARS IN GLOBULAR CLUSTERS

By HALTON ARP

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From 1951 to the present, there has been a continuing effort to observe colors and magnitudes of main-sequence stars in globular clusters. Because of the faintness of these stars this is a difficult observational problem. Nevertheless, we are continuing to obtain these measures in globular clusters because the main sequences afford the only potentially reliable and fundamental calibration of the distance-moduli of the globular clusters. Of course, it is necessary to obtain reliable moduli before one can calibrate the absolute magnitudes of the RR Lyrae stars and the red giants in globular clusters, or compute the ages of the clusters.

One inherent difficulty is the problem of fitting the globular-cluster main sequence to the appropriate metal-poor standard main sequence. At present we take this problem to be primarily one of metallic line blanketing effects in the UBV photometric band widths. Another difficulty is simply that of making accurate color and magnitude measures in the globular clusters at very faint apparent magnitudes. After the main sequence was first located in M92 (Arp, Baum and Sandage 1953), Sandage (1953) observed a long portion of the M3 main sequence. Later Baum

(1954) made observations on the M13 main sequence. The M3 measures were subsequently refined by Johnson and Sandage (1956), and most recently Baum, Hiltner, Johnson, and Sandage (1959) have corrected Baum's original M13 measures. I would like to present results on two new globular clusters, M5 and M2, and compare them with the results on other globular clusters, particularly with the recent measures in M13. The results on M5 are final, although a few more stars may be measured on photographic plates to fill out certain regions of the diagram. The results on M2, however, are very preliminary and are only a schematic approximation of the unsmoothed photoelectric measures.

These results are made possible because we can, as a routine procedure, measure photoelectrically with the 200-inch down to between $V = 20$ and $V = 22$ mag. The aim here has been to get no more than about ± 0.1 mag. accuracy for the faintest stars, but to measure about a dozen of them so that the photographic calibration curve is defined systematically to a few hundredths of a magnitude. For the program, photographic plates have been taken with the 200-inch

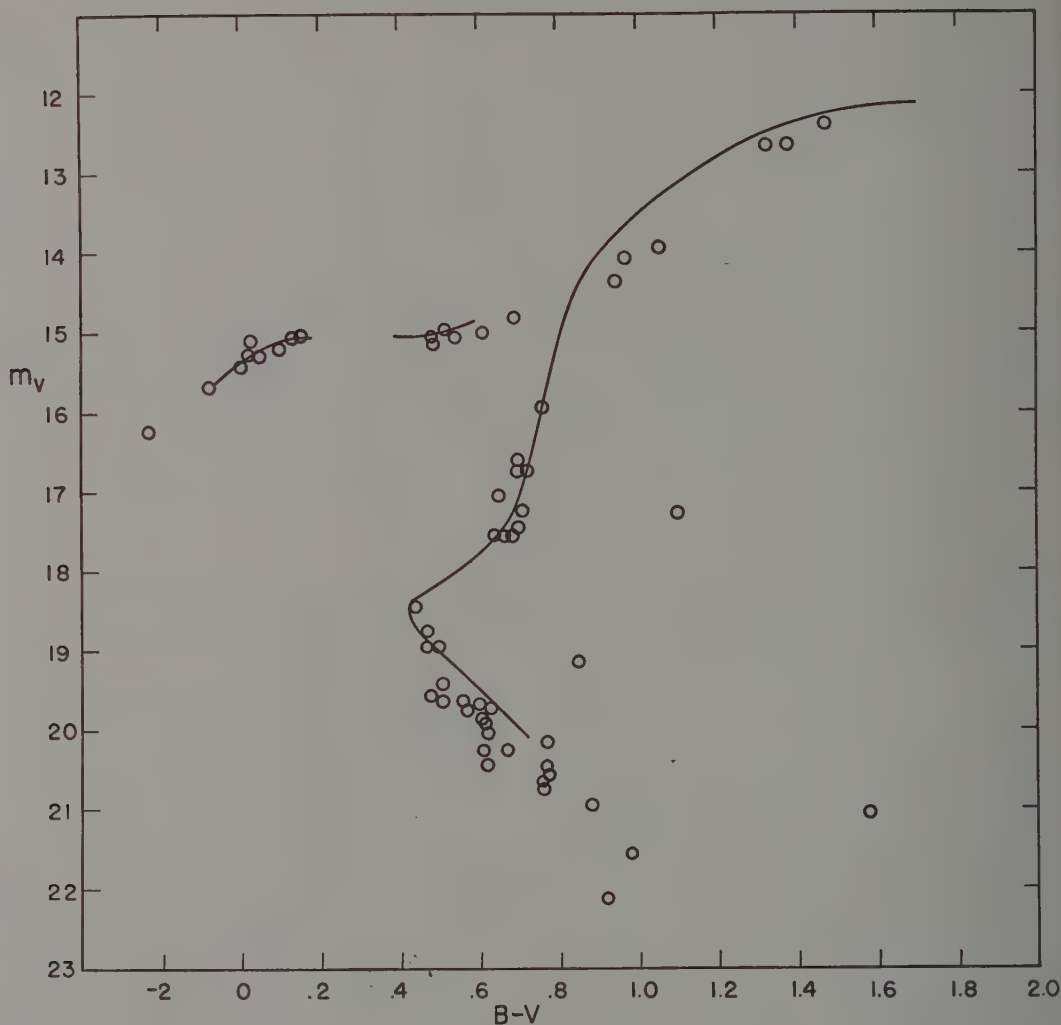


Figure 1. Open circles represent individual stars in M5 which have been measured photoelectrically. Fainter than $V = 18$ mag. the values have been smoothed photographically. The line schematic represents the globular cluster M3 from Johnson and Sandage, and shows both the similarity and difference between the two clusters.

using the Ross $f/4.7$ corrector lens, instead of the usual $f/3.7$ lens. This was to detect and measure fainter stars.

Absolute magnitudes and colors. The color-magnitude diagram for the brighter stars in M5 was obtained primarily by transforming earlier measures (Arp 1955).

The new photographic sample starts at $V = 17.5$ and goes to $V = 20.6$ mag. This sample will eventually be extended to fainter magnitudes to reach the faintest photoelectric standards. In general, the diagram resembles that of M3.

Figure 1 shows the stars in M5 which have been measured photoelectrically. The points are compared to the M3 schematic taken from Johnson and Sandage. The faint stars in M5 have been photographically smoothed. It is obvious that, overall, the clusters resemble each other closely, but there are the following small differences:

- 1) The M5 giant branch is redder—which is in agreement with the slightly greater metal richness indicated by its ultraviolet colors.

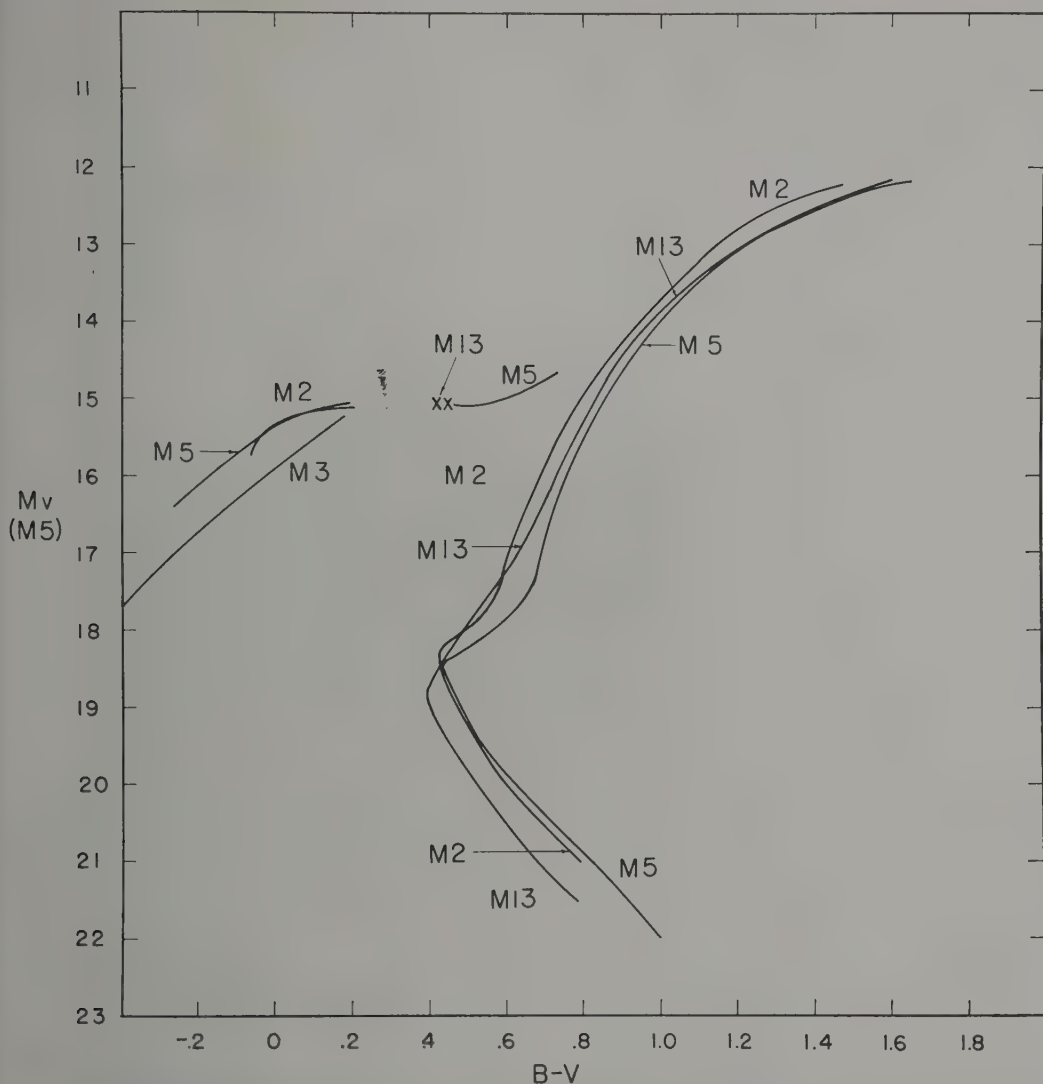


Figure 2. Schematic color-magnitude diagrams for three globular clusters fitted together at the RR Lyrae stars. The diagram illustrates that the observed spread in the position of the main sequences, uncorrected for line-blanketing, is only 0.6 mag.

- 2) The M5 RR Lyrae gap is wider than in M3. In particular, the red side of the M5 gap is 0.08 mag. redder. Probably only a few hundredths of a magnitude could be explained by differential line-blanketing between the two clusters.
- 3) The M5 blue branch extends further to the blue.
- 4) The beginning of the M3 main sequence does not show the steeper rise due to initial

evolution. Because the ultraviolet for these stars also is suspicious, however, it is assumed here that there is a small error in the M3 main-sequence stars.

As an illustration of the present observational status, the schematic diagrams of M2, M5 and M13 are shown fitted together at the variable-star gap in Figure 2 (assuming their RR Lyrae stars all have the same magnitude). This only

serves to demonstrate that, as measured, the color-magnitude diagrams of globular clusters are quite similar. Baum's early results (1954, Figure 3) suggested that the main sequences of such clusters have a spread of about two magnitudes. The present results show that the spread between the three clusters is only 0.6 mag., and this represents our improved accuracy. Because of the different metal abundances, we do not expect them to coincide exactly, however, and we now wish to carefully fit each globular-cluster main sequence to the age-zero main sequence in order to derive a distance modulus.

The two-color diagram for M5 shows that its main-sequence stars have an apparent ultraviolet excess from the standard relation as defined by the Hyades. We assume that if the M5 main-sequence stars had as high a metal content as the Hyades, then they would appear redder in $B-V$ due to the relatively greater effect of line-blanketing in B than in V . Similarly, they would also appear redder in $U-B$, yielding a net apparent ultraviolet excess. The slope of this blanketing line in the $U-B$, $B-V$ diagram has been estimated by Sandage and Eggen (1959) and also by Burbidge, Burbidge, Sandage, and Wildey (1959). They integrated the effect of the metal lines using high-dispersion spectra and computed the change in color due to removing them. Another approach to the problem can be made by using Melbourn's (1959) spectrum-scanner results for the effective temperature of two extreme subdwarfs, HD 19445 and HD 140283. Connecting the observed position of these two subdwarfs in the $U-B$, $B-V$ plane with the corresponding effective temperature of the Hyades 2-color plot gives an independent estimate for the blanketing slope. Except for the sun, the agreement is good enough to make a table which corrects the $B-V$ colors as a function of ultraviolet excess. Using the observed ultraviolet excesses for M5, M13, and M2, we compensate for the line-blanketing effects in $B-V$ and fit to the Hyades age-zero main sequence.

Figure 3 shows the schematic diagrams, corrected for blanketing, for the three globular clusters, all fitted to the Hyades age-zero main sequence. Here no blanketing correction has been applied to stars bluer than A0, that is, the blue end of the horizontal branch, and only half the main-sequence correction has been applied to the red part of the horizontal branch. The whole main-sequence $B-V$ correction has been applied

to the giant branches. We note:

- 1) The absolute magnitudes of the RR Lyrae stars in M2 and M5 are about $M_v = +1$ to $+0.8$ mag. In M13, $M_v = +0.2$ mag. The difference is significant and the question arises as to the luminosities of RR Lyrae stars in other clusters and in the general field.
- 2) The turn up, due to initial stellar evolution, prior to the $S-C$ limit, is clearly shown in all three clusters.
- 3) M5 is the oldest of the three. Based on the recent unpublished evolution calculations by Hazelgrove and Hoyle, its age is about 20×10^9 years (approximate fit by Saltpeter). It turns out that the major difference among M13 and M2 and M5 is one of age, not chemical composition. We shall see that M13 is intermediate in metal strength between M2 and M5. What is different about M13 is that its age, judged by the turn-off point on the main sequence, is considerably younger than M2 or M5. Presumably then, the stars in the upper branches of its diagram, including the RR Lyrae stars, are more massive.

Metal abundance. There has been an exciting and important by-product of this investigation. For the first time it is now possible to establish a parameter which is easy to observe and is an accurate measure of the difference in metal abundance between clusters.

If we look at the color index of $B-V = 1.0$ in the two-color diagram, we realize that this is a luminosity-insensitive point. High metal content or type I stars have $U-B$, $B-V$ relations which pass through this point regardless of whether they are luminosity class I or V. Therefore, this is a definite point of reference. We can compare the globular-cluster giants at this point and postulate that the derived ultraviolet excess is a pure parameter of metal abundance.

Table I gives a confirmation of the accuracy of this parameter. The clusters are arranged in order of their ultraviolet excess read at $B-V = 1.0$ mag. In the second column, the classification assigned completely independently by Deutsch about two years ago from spectra of individual stars in the giant branch is shown. Deutsch's class A is defined as stars showing metal lines only slightly weaker than in normal giants. Class C is extremely metal-poor, and class B is

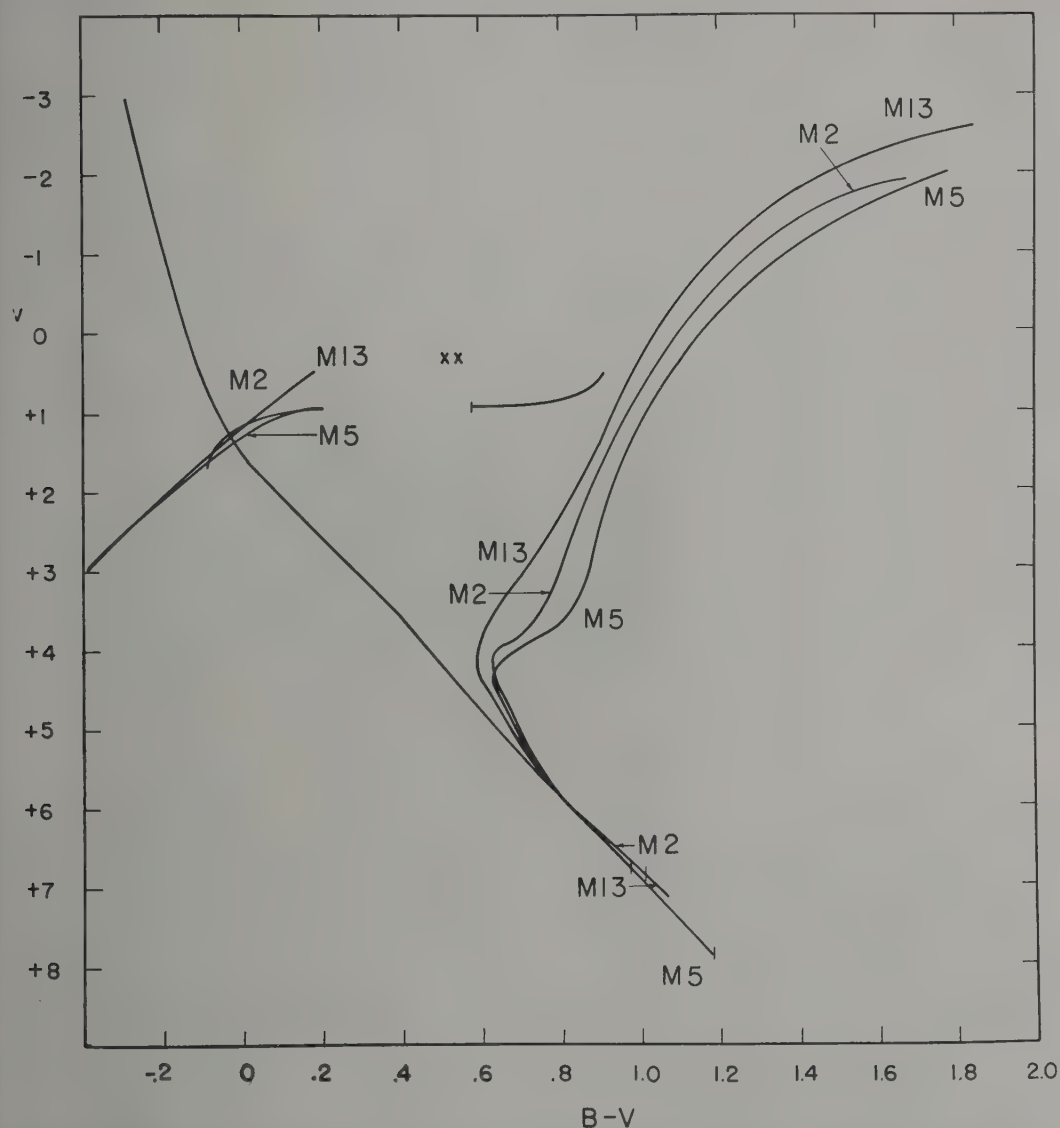


Figure 3. Schematic color-magnitude diagrams for three globular clusters, corrected for line-blanketing at the main sequence and fitted to the Hyades age-zero main sequence. This composite illustrates the differences in age between the clusters and the difference of RR Lyrae absolute magnitudes in M13 relative to M2 and M5. No blanketing correction has been applied to the blue part of the horizontal branch, one-half the correction to the red side, and the full main-sequence blanketing correction has been applied to the giants.

an intermediate group. The next column shows that for the three clusters now having measured ultraviolet excesses on the main sequence, the ultraviolet excess on the giant branch at $B-V = 1.0$ is about 0.05 mag. smaller. This appears to be a constant difference. Preston (1959) has established a parameter of metal abundance by differencing the spectral types of RR Lyrae stars

as determined by their hydrogen lines on one hand and their $H + K$ (metal lines) on the other hand. On a scale from 0 to 10, Preston finds the RR Lyrae stars in M92 have $\Delta S = 9$ to $\Delta S = 10$, and in M5 have $\Delta S = 2$ to $\Delta S = 3$. Morgan's (1959) metallic line groupings from integrated spectra show the same overall correlation. In detail, however, the latter groupings show mis-

TABLE I. METAL ABUNDANCE IN GLOBULAR CLUSTERS

Cluster	$\delta(U-B)$ Giants at $B-V=1.0$	Spectra Giants (Deutsch)	$\delta(U-B)$ m.s. $B-V=.6$	Int. sp. (Morgan)	$\Delta(B-V)$ m.s.	M_v RR Lyrae	b
M5	-0 ^m .15	A	-0 ^m .21	II	0 ^m .14	+0 ^m .8	+ ^o .46
M13	-0.18	A	-0.22	III	0.145	+0.2	+40
M3	-0.20	A to B		II			+78
M2	-0.28	B	-0.33	II	0.20	(+1.0)*	-36
NGC 4147	-0.3	B					+79
Ft. $\oplus$ †	-0.3						+40
M92‡	-0.34	C		I			+35

* Preliminary value, probably will be refined later by a few tenths of a mag.

† New faint globular cluster 16^h09^m +15^o03', Arp and van den Bergh, in press *P. A. S. P.*

‡ The $\delta(U-B)$ value is from an unpublished investigation of M92 by Sandage and Walker.

placements. It would seem to be important to try to account for this in terms of the effect on the integrated spectrum of different distributions in color and magnitude of the stars in the clusters.

It therefore appears possible to measure the metal abundance for any cluster or group of stars which have giants at or near $B-V = 1.0$. Many clusters have such stars, they are bright, and accurate photoelectric measures can be made at very large distances. The chemical composition parameter may then be explored photometrically all over our own Galaxy and into nearby galaxies.

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DISCUSSION OF ARP'S PAPER

DE VAUCOULEURS: Concerning your table of ultraviolet excesses, what corrections for interstellar reddening have been applied to the raw data before the $\delta(U-B)$ were determined?

ARP: No correction for absorption has been applied. As you can see, the galactic latitudes of all clusters in the table are very high. In the case of M5, my three-color observations of field stars near M5 prove that the absorption is $+0.01 \pm 0.02$ mag. For the other clusters we must eventually use the same technique, but the A_v is expected to be small, so the present values in the table are probably nearly correct.

DE VAUCOULEURS: Do you now abandon the view that the reddening can be determined from the position of the RR Lyrae gap?

ARP: Yes. I believe we have more refined methods for determination of the reddening. The position of the RR Lyrae gap is now suspected observationally to vary slightly from cluster to cluster. Therefore, the color boundaries of the gap are probably not precise reddening indicators.

—: What about the absolute magnitude of the RR Lyrae stars in M3?

ARP: We are presently holding the zero-point in M3 in abeyance until a further check is made on the faint photometry.

SANDAGE: I believe our M3 observations are wrong! The error is probably about 0.1 mag in $B-V$ for the faint main-sequence stars. This does not mean that Johnson's photoelectric standards for the faint stars are incorrect. There just are not enough of them to control the photographic interpolation to within ± 0.1 mag. at $V = 20$ to $V = 22$. An error of 0.1 in $B-V$ means an error of 0.5 mag. in $m-M$, and hence an uncertainty of the same amount in the absolute magnitude of the RR Lyrae stars. The M3 data as they now stand give $M_v \approx +1.5$ for the RR Lyrae stars (with blanketing corrections applied to the main-sequence stars). This is too faint in view of Arp's more extensive results in M2 and M5, and in view of $M_v = +0.65$ for RR Lyrae itself, found by Eggen and myself from the moving-group method. We plan new observations in M3 this season to obtain more photoelectric standards.

KRAFT: We have heard a great deal about blanketing corrections in this symposium. Do these calculations include the redistribution of the emergent flux when the lines are taken out? ARP: Yes.

KRAFT: Are there any significant differences in the color of the RR Lyrae stars in M13, and those in M2 and M5, which might explain the difference in the absolute magnitude between the variables in M13 ($M_v = +0.4$) and those in M2 and M5 ($M_v = +0.8$)?

ARP: This is an important point to check. Unfortunately M13 has only two RR Lyrae stars which can be measured at all well. The color measurements were made quite a long time ago and they should be redone with better technique. The observed $B-V$ for these two stars are quite discordant compared with the position of the gap in M2 or M5 (they are too red). I don't know how to interpret this result at present.

—: In your diagram of M5, there is one star in the gap. Is this a variable?

ARP: Eugene Epstein has measured many plates of this star and concludes that if it is a

variable, it has a light amplitude of less than 0.1 mag.

ZIRIN: In making the corrections for blanketing, have the changes in the structure of the atmosphere as the lines are removed been accounted for? The simple blocking of light by the lines is not the only effect on the observed colors.

ARP: The blanketing calculations by Sandage and Eggen include not only the blocking of the radiation, but also the change in the temperature gradient in the atmosphere and the effect of the change in the atmospheric opacity on the emergent flux as the lines are removed.

McVITTIE: In your papers of the last 3 years, you often use $M_v = -0.1$ for the absolute magnitude of the RR Lyrae stars. Should we now adopt $M_v = +0.65$ in reading your work?

ARP: Yes, if you are prepared to accept a possible small adjustment to this value in the next few years.

SANDAGE: But there is great dissension on this point at present. In Oke's paper to be presented at this meeting tomorrow [see *A. J.* 64, 343, 1959], a value closer to 0 is suggested.

GENERAL DISCUSSION

WYATT: I should like to ask Dr. Morgan about the difference in the kinematical solutions between the disk and the halo globular clusters.

MORGAN: The solar motion judged just from the radial velocities appears to be sensibly different, but there are very few clusters in the galactic nuclear region. This is something that should be looked into further.

VAN DEN BERGH: I am a little worried about what changes in the magnitude of the RR Lyrae stars are going to do to the modulus of M31. This would bring the modulus which Mayall obtained by comparison of the globular clusters in our own Galaxy and in M31 to below 24, and aren't we going to get into trouble with the modulus of M31 found from the Cepheids?

SANDAGE: But isn't it true that the RR Lyrae stars have not been directly observed in M31? As you point out, however, there is an indirect connection by using the globular clusters in our own Galaxy and comparing them with the clusters in M31. The integrated absolute magnitudes of the clusters in our Galaxy which Mayall used for this comparison become fainter by 0.6 magnitudes, but the recent work on the zero-point

of the classical Cepheids in galactic clusters in our Galaxy also shows that these stars must be made fainter by about 0.6 magnitudes from Baade's and Blaauw's zero-point. This difference in zero-point between the classical Cepheids and the RR Lyrae stars remains at 1.5 magnitudes by the double revision, and so no new discrepancy should arise in $m - M$ for M31. The modulus will decrease by 0.6 magnitudes using either the classical Cepheids or the globular clusters.

McVITTIE: Mr. Chairman, as I am a bit confused at this point, could we summarize? It seems that the globular clusters in our Galaxy can be divided into two or more categories—those having weak metal lines and those having strong metal lines. In thinking over what the speakers have said about M31 and the Magellanic Clouds, I gather that this sort of division has not been observed so far. Is this correct?

SANDAGE: Hodge's color-magnitude diagram of NGC 1978 in the Large Magellanic Cloud, which was presented this morning [see *A. J.* 64, 335, 1959], appears to have a slope to the giant branch which is much less steep than the metal-weak globular clusters in our own Galaxy.

Hodge's C-M diagram for NGC 1978 resembles somewhat the diagram for NGC 6356, which is the metal-rich globular cluster near our own galactic nucleus. You might presumably believe that this fact, together with the C-M diagram for NGC 1783 in the Large Magellanic Cloud obtained by Eggen and myself during the last season at the Radcliffe Observatory in South Africa, together with Arp's peculiar clusters NGC 419 and NGC 361 in the Small Magellanic Cloud, might indicate metal-rich clusters in the main body of the Clouds; but certainly the clusters NGC 121, NGC 1466, and NGC 2257, which all have a large number of RR Lyrae stars, look like the halo globular clusters. The relative positions of these clusters is such that NGC 361, 419, 1783, and 1978 are projected onto the main body of the Clouds, while NGC 121, 1466, and 2257 are in the outskirts and might be considered as "halo" objects from their positions. So maybe there is a division between the metal-poor and the metal-rich clusters in the Magellanic Clouds, divided according to whether they are outlying or are in the main body of the Clouds. But maybe not, too.

McVITTIE: And M₃₁?

SANDAGE: Well, presumably you would have to go on the integrated colors or spectral types here, and we do not know the answer yet.

POPPER: I would like to ask a question of Dr. Arp. As I understand his approach in matching the color-magnitude diagrams of M₂, M₅, and M₁₃ to the Hyades, first correcting the colors for blanketing based on observations of the UV excess, and then assuming that he can align these, I wonder if the results of Mr. Demarque [see *A. J.* 64, 327, 1959] this morning on the internal constitution changing according to metal content might not make one worry a little about this observational approach. The luminosity for stars of different metal content has quite a range for stars of the same mass, so lining up the main sequences in this way presumably aligns stars of the same mass but with different metal content from cluster to cluster.

ARP: That certainly does come in, but I think that the difference in main sequences is at most 0.2 magnitude because the effect of low metal abundance with corresponding low *He* abundance tends to push the main sequences in opposite directions, and the two abundance parameters tend to cancel each other in their effect on the main sequence. At present our accuracy is not quite 0.2 magnitude in these fits.

POPPER: But isn't the effect of Demarque that stars of the same mass but different composition differ in luminosity by two magnitudes?

ARP: Yes, but we do not fit by comparing stars of the same mass, but rather by comparing colors and luminosities. The effect in the M_V vs. $\log T_e$ diagram is only 0.2 magnitude, but the luminosity assigned to a given mass can vary by 2 magnitudes. This mass effect will change the calculated ages but not the derived photometric moduli by more than 0.2 magnitude at the most. While on my feet, I would like to comment on the earlier discussion between McVittie and Sandage on differences between clusters in other galaxies. They were discussing rather subtle differences among the red clusters, such as NGC 361 and 419 in the Small Magellanic Cloud, and NGC 1978, 1783, 121, and 2257 in the Large Magellanic Cloud—differences which at present are observationally uncertain, but the *outstanding* differences in clusters in the Magellanic Cloud use the sharp division into red and blue clusters both of which look like rich globulars on the photograph; this striking difference shows up between NGC 1866 (blue) and the clusters which Sandage discussed with McVittie. This division between red and blue clusters can be explained keeping for the moment the chemical composition constant, by the effect of stellar evolution. As the blue clusters with bright O and B stars get older, these O and B stars will burn off and you get a range of blue clusters going down in magnitude. Then the resolution of the cluster disappears from the photographs because the stars fall fainter than the plate limit; but when the clusters get old enough, the red giant branch will peek above the plate limit because of the upward trend of the evolutionary tracks, and the red globulars will be seen. The blue clusters therefore evolve into the red clusters and the striking observed difference is primarily one of age.

MORGAN: In the course of this symposium we have had additional evidence of the great range in physical properties which is encountered in various globular clusters. If we add to this the information on M67, we can see that the problem of definition—or separation—of separate kinds of clusters is a very real one. M67 itself probably has to be considered a disk cluster rather than a spiral-arm cluster, but we now know that certain globular clusters also have to be identified with the galactic disk. I should like to ask Dr. Sandage whether he now thinks that the cluster phenomenon

enon might be considered a general one, all the way from such clusters as M13, where on the average we have a very rich cluster of large mass, through M67 to the other extreme—say the nuclear region of O associations. In Sandage's opinion, is the evidence in favor of this interpretation?

SANDAGE: The answer seems to depend on the definition of galactic and globular clusters.

MORGAN: Yes. Can you define globular clusters as a group, as distinct from galactic clusters?

SANDAGE: Well, before Arp wrote the *Handbuch* article on the H-R diagram, we used to talk about an unambiguous definition of globular and galactic clusters. I used to say that I thought the definition should be based on the color-magnitude diagram, but he pointed out the strange differences between so-called globular clusters like NGC 6838, with no horizontal branch at all, and Abell's 11-hour cluster with a stubby horizontal branch. So the real question became: Is a globular cluster defined by the concentration of stars in some dynamical grouping, or is it defined by a color-magnitude diagram? Part of the confusion in trying to take into account all of the properties of clusters comes because one school defines clusters in terms of dynamical or spatial distributions, while another school defines clusters in terms of color-magnitude diagrams. Now there is a very curious separation between massive and open clusters. Stars in M67 are old, just like those in M2, M3, M5, and M13. Defined by the break-off point of the main sequence, you can tell very little difference in ages. But it seems very strange that those clusters which are so massive (10^5 to 10^6 solar mass) are also so metal-poor—more metal-poor than M67. I don't think we know any so-called "open" cluster which has a low metal abundance, so there seems to be some correlation between the metal abundance and the total number of stars in the cluster. This we do not really understand; it is not an age difference. But somehow the number of stars which have formed must depend on the chemical composition, or maybe on an independent parameter that both composition and mass are related to, such as position in the galaxy.

MORGAN: You recently have studied another "open" cluster which is older than M67?

SANDAGE: Yes. Ivan King in 1948 and van den Bergh in 1957 pointed out that NGC 188 should be old, like M67. Van den Bergh got a luminosity function for NGC 188 which suggested that it would be similar to M67. The

present study shows that the color-magnitude diagram of 188 has a shape identical to that of M67. The M_v normalization for 188, which van den Bergh got from measurements last summer at Mount Wilson, has been confirmed by more extensive measurements this year, and shows that NGC 188 is 1.2 magnitudes fainter than M67 in the M_v , $B-V$ diagram. But from the UBV photometry, the stars in NGC 188 are *metal-rich*, even though 188 is as old or older than the metal-poor "globular" clusters such as M2, M5, and M13.

MORGAN: Suppose one were making a new catalogue of clusters, what would be the natural separation of clusters between "open" and "globular?"

SANDAGE: Well, I really don't know. I would ask Mrs. Hogg—she is the expert. Her lists are definitive.

ARP: I have a personal preference in this matter which stems from Baade's original definition of population types. He defined Population II in terms of the color-magnitude diagram of a "normal" globular cluster. This has gone over in a very natural way into the parameter of metal abundance, so it seems to me to be natural to say that globular clusters are defined to be clusters with low metal abundance, and the galactic clusters are those of high metal abundance, even though the open clusters may also have a spherical appearance and be quite populous.*

* (Editor's note: The following comment by Arp was added after the Toronto meeting.)

Originally, the name "globular cluster" defined a class of objects by their geometrical appearance. Now, however, age and chemical composition have become more significant for classification purposes. These physical properties are exhibited in the color-magnitude diagram, which seems more important from the evolutionary standpoint than the geometrical or dynamical arrangement of stars within the cluster.

Since the introduction of the term "Population II," the term globular cluster came to primarily designate a specific and characteristic color-magnitude diagram, but recently we have encountered star clusters in our Galaxy and in other galaxies which are globular in their geometrical appearance, but which contain stars of differing age and chemical composition (e.g., NGC 1866 in the LMC).

Obviously, we need to expand our terminology in order to discuss the new data accurately. We have a choice of redefining terms or of creating new ones. It would seem out of the question to return the term "globular cluster" to its logical original role of describing a cluster's geometry. Few astronomers, for example, would care to think of η and χ Per as "globular clusters" despite the fact that they are fairly rich and spherical in form. It would seem necessary today rather to talk about *star clusters* whenever possible. It is now well recognized that star clusters may contain stars which run the gamut of age and chemical composition. The original well-known globular clusters, such as M3, M13, and ω Cen, happen to be examples con-

DE VAUCOULEURS: We seem to have here a problem which is similar to one familiar to zoologists and biologists in taxonomy. The definition of a species is a group of animals or plants that share the same characteristics. These are agreed to form a species according to a competent taxonomist. There seems to be no limit to any species, and it may be a problem which is not very meaningful to try to pin down a sharp boundary between a globular cluster and a galactic cluster. When we have measured hundreds of clusters, there may be a whole spectrum of color-magnitude diagrams.

SANDAGE: Well, right now do you know any cluster that would be intermediate, which you would question on either the basis of the

taining metal-poor old stars. Usage will continue to refer to them as "globular clusters." It would be a mistake, however (a mistake made by the writer, among other, in the past), to refer to star clusters in the Magellanic Clouds as "globular clusters." Such star clusters are characterized by more than one set of subsidiary characteristics, such as the color-magnitude diagram, shape, and richness.

projected appearance on the plane of the sky or the diagram where you would put it?

DE VAUCOULEURS: I heard Arp asking about some of the clusters in the SMC with a break in the subgiant branch, and whether this makes them globular or not globular. Also, we heard from Cuffey this morning about NGC 6838. It may be that if you start from a large population and use only two or three objects as a sample, then you have a pure classification; but if you have hundreds of them, it may not be so simple.

CONCLUDING STATEMENT BY MODERATOR

The tenor of the papers has been to show that within our Galaxy and in external galaxies the globular clusters show tremendously diverse characteristics in integrated spectra, in intrinsic colors, in periods of the RR Lyrae stars, in appearance, and in the shapes of the color-magnitude diagrams. The problem of interpretation appears to be more complicated than we thought only a few years ago.

THE RELATION BETWEEN ASTEROIDS, FIREBALLS AND METEORITES¹

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Abstract. Asteroids, meteorites and fireballs with visual magnitude $M < -5$ are shown to have the same mass distribution. Bright fireballs are therefore asteroidal debris, whereas the fainter meteors originate in the nuclei of comets. The influx of cometary meteors equals the influx of asteroidal meteors at a visual magnitude of -3 . The percentage of asteroidal meteors varies from 90 per cent at magnitude $= -10$ to 7 per cent at magnitude $= +5$. A fireball of magnitude -10 travelling with a velocity of 17 km sec^{-1} has a mass of 40 kg on entering the earth's atmosphere and produces a meteorite weighing approximately 10 kg. The earth on the average encounters 3.3 fireballs per day with magnitude ≤ -10 and collects an asteroidal fragment with mass $\geq 4,000$ tons every hundred years.

1. *Introduction.* The majority of meteors seen by a visual observer come from the icy nucleus of a comet, whereas the larger meteorite fragments found on the surface of the earth result from the break-up of asteroids. Theoretical considerations by Whipple (1951) show that large particles will not be ejected by comets. Thus we are led to expect that the meteor population is composed almost entirely of asteroidal chips at some point in the magnitude scale. This paper presents a study of the mass distribution of asteroids, meteorites and fireballs in an attempt to uncover any differences in the populations.

2. *Asteroids.* A recent survey of asteroids by Kuiper *et al.* (1958) has established that the number of asteroids, dN , with absolute magnitudes between M_0 and $M_0 + dM_0$, is given by the exponential law,

$$dN = ar^{M_0} dM_0, \quad (1)$$

where a is a constant and r is the ratio of increase for an increment of one magnitude. We shall call

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equation (1) the incremental law; it may be integrated to give the cumulative law (Hawkins and Upton 1958),

$$\log N = N_0 + M_0 \log r, \quad (2)$$

where N is the number with magnitudes between M_0 and $-\infty$ and N_0 is a constant, $N_0 = \log a \log (\log_e r)$. Logarithms are to the base 10 unless otherwise specified.

The distribution may be expressed in terms of the radius, ρ , of the asteroid by the substitution $M_0 = \text{constant} - 2.5 \log \rho^2$.

Equation (2) then becomes

$$\log N = N_0 - 2.5 \log r \log \rho^2. \quad (3)$$

To express the distribution in terms of the mass, m , of the asteroid we substitute the relation $M_0 = \text{constant} - 2.5 \log m^{2/3}$ in equation (2) to give

$$\log N = N_0 - 1.67 \log r \log m. \quad (4)$$

Finally, the distribution may be given in terms of the visual magnitude, M , that the particle would produce if it ablated in the atmosphere of the earth. To do this we may use an equation of the meteor theory (Hawkins and Southworth 1958, eq. (2)) and assume that the particles have constant velocity and angle of approach in the atmosphere. Then $M = \text{constant} - 2.5 \log m$, and substituting this expression in equation (4)

yields

$$\log N = N_0 + 0.667 M \log r. \quad (5)$$

It will be realized that N_0 in equations (2), (3), (4), and (5) represents a different numerical value in each equation.

The survey of Kuiper *et al.* (1958) showed that the average value of $\log r$ was 0.56 and there was a spread of values between 0.35 and 0.73 for different asteroidal zones. If we take $\log r = 0.60$, then the cumulative distribution laws are as follows:

for radius, ρ , as variable,

$$\log N = N_0 - 1.5 \log \rho^2; \quad (6)$$

for mass, m , as variable,

$$\log N = N_0 - \log m; \quad (7)$$

for visual magnitude, M ,

$$\log N = N_0 + 0.4 M. \quad (8)$$

Differentiation of the cumulative laws leads to the incremental laws:

for radius, ρ , as variable,

$$dN = \frac{a}{\rho^4} d\rho; \quad (9)$$

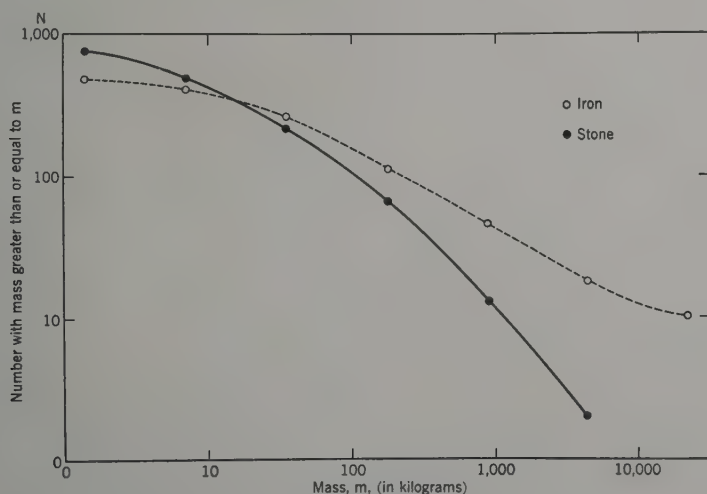


Figure 1. Cumulative mass distribution of meteorites.

for mass, m , as variable,

$$dN = \frac{a}{m^2} dm; \quad (10)$$

for visual magnitude, M ,

$$dN = a 2.5^M dM, \quad (11)$$

where a is an arbitrary constant. Thus in extrapolating the asteroidal data to the realm of meteorites and fireballs we would expect an increase of 2.5 in the number of fireballs for a decrease in brightness of 1 magnitude. Also if the meteorites at present in our museums are classified according to mass, the number of specimens with mass $\geq m$ should vary inversely with the mass.

3. *Meteorites.* Data on the mass of meteorites have been collected by Prior and Hey (1953), whose catalog lists 1380 meteorites with known masses. In Figure 1 the cumulative number, N , is plotted as a function of the mass, m , in kilograms, for iron and stone meteorites. The gradient of the curve for stones approaches -1.0 . The difference between stone and iron distributions is probably not a real effect; the curves for iron "falls" agree with the stones and the deviation is produced only when iron "finds" are included. A gradient of -1.0 agrees with the mean

value found for asteroids by Kuiper *et al.* and the data are consistent with the assumption that meteorites are asteroidal bodies. The curves in Figure 1 deviate significantly from a straight line for $m < 10$ kilograms, because of the difficulty in finding the smaller bodies.

4. *Fireballs.* The magnitude distribution of bright meteors has been determined by visual observing teams in the United States, Great Britain, and Canada. In Figure 2 the number of meteors with visual magnitudes brighter than a chosen value of M has been plotted as a function of that value. The British results were obtained by simultaneous observations from different sites and the magnitudes have been corrected for the effect of the inverse square law (Hawkins and Prentice 1957). The distribution curve obtained by the American Meteor Society has been found from 71,431 observations supplied by Dr. C. P. Olivier (private communication and 1959), where the brightness is given as the apparent magnitude. The distribution is linear between magnitudes of -10 and -3 with a gradient of 0.4 . This is consistent with equation (8) and supports the assumption that fireballs are composed of asteroidal debris. Approximately 30 per cent of the meteors belonged to recognized streams, but the number of these cometary meteors with $M \leq -3$ is presumably small and their inclusion has not affected the observed gradient. The re-

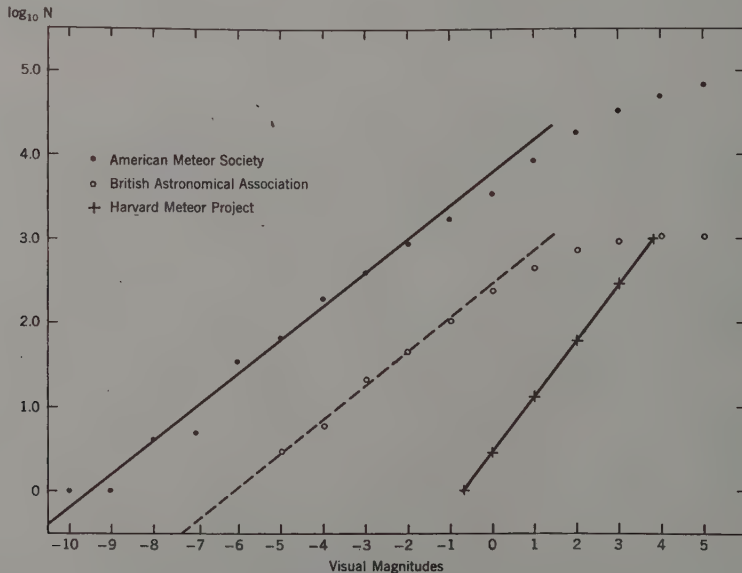


Figure 2. Cumulative magnitude distribution of fireballs and fainter visual meteors.

sults reported by the British Astronomical Association (B.A.A.) are for sporadic meteors only and confirm this conclusion. It should be noted that we have assumed the collecting area for a visual observer to be constant for bright meteors. This assumption will be discussed in a later section. The curvature of both the A.M.S. and B.A.A. distributions at the fainter magnitudes is due to the decreasing efficiency of detecting faint meteors.

Canadian observations (Millman and Burland 1957), which are not shown in Figure 2, give a gradient of 0.57 between magnitudes of -6 and 0 . This result does not agree with the British and U. S. data; the reason for the discrepancy is not yet known. Difficulties exist in estimating the brightness of fireballs when no standards of comparison are available. The magnitude scale of the British Astronomical Association is probably the most reliable standard since the magnitudes were determined by direct comparison with a star or planet. Furthermore, the brightness was determined independently by observers at two or more sites and the sample does not extend far into the region where comparison standards are not available. The discrepancy could be accounted for if Canadian observers tended to underestimate the magnitude of bright meteors; this explanation would also account for the fact that, whereas the Canadian and U. S. observers recorded comparable numbers of meteors, the Canadian observations do not record any meteors with magnitude < -6 . As an alternative explanation the sample may include a large number of stream meteors. This alternative is supported by the fact that the gradient decreased to 0.45 when 2027 sporadic meteors were analysed as a separate group.

For comparison, the Harvard photographic observations (Hawkins and Upton 1958) are included in Figure 2, which shows that between magnitudes of 0 and $+4$ the gradient is 0.537. The probable error of this determination is ± 0.02 and the gradient is significantly different from the fireball distribution. Thus the visual and photographic results show that for $M < -5$ the ratio of increase is 2.5 per magnitude and for $M > 0$ the ratio of increase is 3.4 per magnitude.

5. *Discussion.* The work of Kuiper *et al.*, the study of the mass of meteorites, and the observations of American and British meteor teams show that the masses of asteroids, meteorites and fireballs show a similar distribution. We may infer that most fireballs brighter than magnitude -5 are fragments of stone and/or iron that have

been ejected from the asteroid zone. Meteors with visual magnitudes fainter than zero have a different mass distribution. This group contains both the well-defined streams and sporadic meteors in scattered orbits. We are certain that meteor streams have been ejected from the nuclei of comets, and it is probable that sporadic meteors have been perturbed or diverted from the established streams by the several sources of perturbation that are present in the solar system (Whipple and Hawkins 1959). We may therefore logically attribute a cometary origin to meteors fainter than magnitude zero. These cometary particles possess a low specific gravity, and fragment on entering the atmosphere (Jacchia 1955). It is interesting to consider the magnitude at which asteroidal and cometary particles are observed in equal numbers. In the present paper we show that the limits of the transition zone are $-5 < M < 0$, and in the following discussion we shall adopt -3 as the visual magnitude where the influx rates of the two populations are equal.

The cometary component predominates in the Harvard photographic results (Hawkins and Upton 1958), which show that

$$\log N_c = 0.537 M - 5.17, \quad (12)$$

where N_c is the number of cometary meteors with a visual magnitude brighter than or equal to a chosen value of M , incident on one square kilometer of the earth's atmosphere per hour. The influx rate of asteroidal meteors, N_a , is obtained by putting $N_a = N_c$ at $M = -3$:

$$\log N_a = 0.400 M - 5.58. \quad (13)$$

The ratio of cumulative numbers of asteroidal and cometary particles is given by the expression

$$\log \frac{N_a}{N_c} = -0.137 M - 0.41, \quad (14)$$

and the ratio of numbers between magnitudes M and $M + dM$ is given by the expression

$$\log \frac{dN_a}{dN_c} = -0.137 M - 0.54. \quad (15)$$

From equations (14) and (15) we can compute the percentage of meteors that have an asteroidal origin at various visual magnitudes; these percentages are given in Table 1.

TABLE I. PERCENTAGE OF METEORS WITH ASTEROIDAL ORIGIN

Visual magnitude	Meteors with visual magnitude $\leq M$	Meteors at visual magnitude M
-15	98%	97%
-10	90	87
-5	65	58
0	28	22
+5	7	6
+10	2	1

We may now deduce the rate at which meteorites reach the atmosphere of the earth, by expressing equation (13) in terms of the mass, m , of the body. The original meteor theory was based on the assumption that the meteor particles were solid fragments with densities between 3 and 8 gm cm⁻³. This assumption is valid for the asteroidal fragments. Whipple and Hughes (1955) have shown that the average velocity of meteorites in the earth's atmosphere is 17 km/sec. Whipple (1954) has derived the masses of bright meteors from a numerical integration of the light curve; thus a fireball with $M = -10$ and $V = 17$ km sec⁻¹ has a total mass of 40 kilograms. This relation enables us to transform equation (13) into the form of equation (7), and the influx law as a function of mass becomes:

$$\log N = -\log m_{\infty} - 7.98 \text{ km}^{-2} \text{ hour}^{-1}, \quad (16)$$

where m_{∞} is in kilograms and is the mass before ablation. Thus 3.3 meteorites enter the atmosphere per day with a mass, $m \geq 40$ kilograms, and produce fireballs of magnitude -10 or brighter. This figure is consistent with the tentative estimate of Watson (1956), who concluded that five meteorites per day arrived at the surface of the earth with an average mass after ablation of 20 kilograms. From equation (16) we may estimate that the earth receives one meteorite with a mass (before ablating) of 4,000 tons every 100 years. It would be of interest to verify this influx law by obtaining estimates of brightness of meteorites that have been observed to fall, but observations of this nature have so far been found inadequate.

The influx rates of fireballs and meteorites have been derived by assuming that the numbers of asteroidal and cometary meteors are equal at a visual magnitude of -3 . It is not possible to

derive an influx rate for fireballs directly from the observations because the collecting area of a visual observer is not known. One can, however, reverse the procedure and derive the collecting area from the observed hourly rates and equation (13). The mean rate obtained for observers of the American Meteor Society is 12 per hour (Olivier 1958). A total of 5,953 hours of observing time was therefore required to observe the 71,431 meteors described in Section 3, and the observed rate for meteors with $M \leq -5$ was 0.0128 hour⁻¹. From equations (12) and (13) we predict that 3.33×10^{-8} meteor with $M \leq -5$ pass through 1 square km per hour. Thus a visual observer has a collecting area of 384,000 km² for meteors brighter than -5 . This extremely large area shows that a visual observer covers the entire sky from the zenith down to an altitude of 10°. It is well known that an observer sees bright meteors even when he is not looking in the correct direction—the meteor reveals its presence by a general increase in sky brightness and by shadows that are cast on the ground. Thus we may assume that the collecting area, and hence the observing efficiency, remain constant over the magnitude range of -5 to -10 , and no systematic errors are to be expected in the magnitude distribution shown in Figure 2.

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DIFFRACTION PATTERNS PRODUCED BY OBSTRUCTIONS IN REFLECTING TELESCOPES OF MODEST SIZE

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Abstract. The presence of a secondary mirror and its supports in a reflecting telescope causes considerable changes in the diffraction pattern which is the image of a star. Drawings are presented which show in detail the modification of this pattern caused by central obstructions of various diameters. The fraction of the energy in the central disk of the pattern is calculated and this is found to decrease as the opaque central stop is made larger. The resulting deterioration in contrast is discussed. The diffraction spikes caused by supporting members of various widths and orientation are illustrated. In particular, the case of a central stop with four supporting struts is discussed in detail. The designs recommended for improved definition and contrast are those in which the obstructions have a minimum of area. Because of atmospheric seeing effects the results of this study are applicable primarily to telescopes of apertures less than about 20 inches used for high resolution studies under excellent seeing conditions.

1. INTRODUCTION

When parallel light from a star enters a telescope with a clear circular aperture, the focused image of the star under ideal conditions is the familiar Airy disk surrounded by several rings. The pattern becomes more complicated, however, when there are obstructions in the light path. For example, in the Newtonian telescope, as shown in Figure 1, the small secondary mirror and its supports cause interesting modifications in the diffraction pattern. Except in the rather uncommon off-axis designs, similar obstructions are to be found in all reflecting telescopes. In this paper the diffraction patterns resulting from a wide variety of obstructions which are likely to be found in reflecting telescopes are shown and discussed.

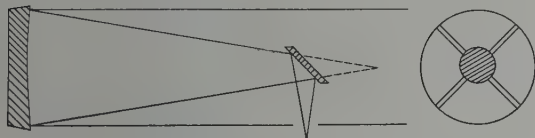


Figure 1. Newtonian telescope showing obstructions in the light path.

There are many telescopes which are perfect in the sense that the resolution is not limited by geometrical aberrations of any kind. For these, the resolution is fundamentally limited by two factors. The first factor is the "seeing" which depends upon the steadiness and uniformity of the atmosphere and which becomes worse as the aperture is increased. The second factor is the diffraction pattern which improves, becoming smaller, as the aperture is increased.

For large telescopes the diffraction pattern is almost invariably smaller than the image size caused by the seeing, the so-called seeing disk. For example, the 200-inch Hale telescope has a diffraction pattern which is about 0.05 second of arc wide between minima on either side of center. The seeing disk for this aperture is much larger than this. The star images are spread over an area which usually exceeds one second of arc in diameter. For large telescopes the details of the diffraction pattern are thus of little interest. However, for telescopes with apertures smaller than about 20 inches, the resolution may occasionally be limited by diffraction when excellent seeing obtains.

There have been a number of excellent theoretical treatments of the clear and annular aperture as noted in Section 4 below. However, the work of the present paper is experimental and is not limited to the annular aperture. A study of these diffraction effects may lead to the better design of reflecting telescopes of modest aperture for high resolution visual work.

Other experimental studies of diffraction patterns include that of Sheiner and Hirayama (1948) who photographed diffraction patterns for apertures of many unusual shapes. More immediately relevant is the work of Dall (1938) who has presented photographs of the diffraction patterns for a circular aperture with circular opaque central stops of various diameters, and has discussed the effects of such obstructions on resolution of planetary detail and on separation of close double stars. The work presented here is, in some respects, an extension of the work by Dall.

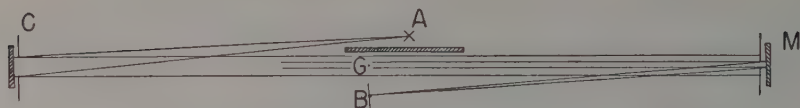


Figure 2. The optical system used to photograph the diffraction patterns.

2. OBTAINING THE DIFFRACTION PATTERNS

a. *The optical system.* The optical system used to photograph the diffraction patterns is shown in Figure 2. The image of the filament of a small incandescent lamp was focused by a small condensing system on a pinhole at A made in aluminum foil. The pinhole was placed one focal length away from a collimating mirror C. This produced a parallel beam simulating starlight striking mirror M, which will be called the telescope mirror. An image of the pinhole was formed at B. By suitably stopping the telescope mirror, a diffraction image was formed which was large enough to photograph. A camera was placed so that the focused image fell on film at B. The shutter of the camera was used to control the exposure, but of course the lens was removed. The film was Kodak Panatomic-X, a fine-grained emulsion.

The tungsten filament source, used in combination with this panchromatic film, permitted a range of wavelengths extending across the visible spectrum to contribute to the diffraction image. When the camera was removed the image could also be examined visually with an eyepiece. There were colored fringes in the outer parts of the pattern which made it more complicated than patterns made with monochromatic light.

Both mirrors had a focal length of ten feet and were four inches in diameter before stopping down. The collimator mirror C was stopped to an aperture of 2 inches which was large enough so that it did not act as an aperture stop. The aperture of the telescope mirror M was closed to 0.500 inch. The linear width of the diffraction pattern (between first minima on either side of center) at the 120 inch focal length was approximately 0.0130 inch for wavelengths in the middle of the visual spectrum. The pattern was very well resolved on the film used. The pinhole at A had a diameter of 0.0018 inch and its geometrical image at B was the same size. This is small enough in comparison to the size of the diffraction pattern to be effectively a point source.

The figure exaggerates the angle at which the mirrors were tipped; to be in scale the horizontal dimensions should be increased several times.

The geometrical aberration caused by tipping the mirrors has been calculated and this would produce a circle of confusion of only 0.0030 inch, which is negligible here. It seemed advisable to use mirrors rather than long focus lenses because they are perfectly achromatic and the folded path allowed the experiment to be done in a smaller space.

b. *Photographs and drawings.* The original negatives had excellent detail of both the central region and the faint outer parts of the diffraction pattern. However the range of density was much too large to be shown on a single print. The central region has about 625 times the intensity of the fourth bright ring, for example. Prints exposed so as to show the faint outer detail showed no detail in the central region (not even the first dark ring was visible), and prints exposed to show the central region in proper contrast showed none of the faint outer detail.

An attempt was made to prepare a series of prints which compromised the above extremes, but this was, on the whole, unsatisfactory. Much of the interesting detail was lost completely. Our solution to the problem was to prepare pencil sketchings which were tracings of two prints of each pattern, the one print exposed to show the inner region, the other print exposed to show the faint detail. Within a limited scale an attempt was made to show intensity gradations consistently. The drawings were done with a soft black pencil on white paper and reversed photographically so that they appear white on black.

The single exception to the above procedure is Figure 4 which, in that case, shows actual photographs printed so as to show the central region.

3. POSITION OF THE DIFFRACTING OBSTRUCTION

In most reflecting telescopes the obstruction is located almost a full focal length in front of the mirror, but in simulating these designs and discussing the theory, it would be most convenient if the obstruction could be placed directly on the face of the mirror. It was important to decide whether the diffraction pattern would be the same in either case.

The theoretical answer to this question was not immediately evident and a direct experiment was performed to determine the answer. An obstruction consisting of a rod of diameter 0.060 inch was placed across the center of the collimated light beam at G, Figure 2, one focal length in front of M and a photograph taken. Another photograph was taken with the same obstruction immediately adjacent to the mirror M. The two photographs were identical and appear in Figure 4 (a, b).

This result was confirmed in another experiment: One rod was placed in a vertical position at G and a second rod was placed in a horizontal position at M. If the placement of the obstruction were critical, then the diffraction pattern would not be symmetrical. The photograph of Figure 4 (c) shows, however, a symmetrical pattern. Evidently the distance between the obstructions and the telescope mirror is not critical here. Unless otherwise noted, the obstructions in the experiments to follow were placed on the face of the telescope mirror.

4. CIRCULAR CENTRAL STOPS

The commonest type of obstruction to be found in reflecting telescopes is the secondary mirror which acts as an opaque circular central stop. Although the diffraction pattern in this case of an annular aperture is readily calculable, it was thought that the progressive changes in pattern should be shown pictorially as well.

a. *Experiment.* The central stops were simulated by brass plates of various diameters mounted concentrically in the 0.500 inch aperture of the telescope mirror M. Each stop was held in place by four glass fibers only 0.0012 inch diameter. Although the effect of such struts would be to cause spikes to appear in the diffraction pattern, as discussed later in this paper, these glass fibers were too small to cause discernible spikes in the photographs.

Figure 5 shows the patterns obtained and scale drawings of the aperture for each case. Under each drawing is given the value of a parameter α , which is the ratio of the central stop diameter to the aperture. The sequence shows patterns for $\alpha = 0, 0.10, 0.15, 0.20, 0.25, 0.30, 0.40$, and 0.75. For $\alpha = 0$, there is no central obstruction and the familiar Airy diffraction pattern is obtained. The changes in the ring structure are interesting. As α increases from zero the first ring increases in intensity. The second ring decreases in inten-

sity up to $\alpha = 0.25$ and then increases until it is very strong at $\alpha = 0.75$. Systematic changes in the other rings can be seen.

b. *Theory.* The intensity distribution in the above patterns can be compared with formulae obtained by Airy (1835) for this case. (Airy's treatment includes both the clear and the annular case. Modern derivations are given by Lord Rayleigh (1910), and by C. C. Steward (1925).) The intensity I is expressed in terms of Bessel functions J_1 , of the first kind and order unity:

$$I = \left[\frac{a^2 k u_0}{2F} \right]^2 \left[\frac{2J_1(r)}{r} - \frac{a^2 2J_1(\alpha r)}{\alpha r} \right]^2. \quad (1)$$

Here a is the radius of the aperture, k is 2π divided by the wavelength, u_0 is the field of the incident wave in the plane of the aperture, F is the distance between the aperture and the image plane, and r is a dimensionless radial coordinate in the image plane. Specifically, r equals kaR/F where R is the actual radial distance in the image plane. The systematic changes in ring structure shown in Figure 5 are predicted by Equation (1). The above result is for the intensity in the focal plane. The general case for the annular aperture, including planes inside of and outside of focus, has been calculated by Linfoot and Wolf (1953).

It is interesting to calculate how much of the total energy lies within the central disk for each value of α . Lord Rayleigh (1910) made this calculation for $\alpha = 0$ and Dunham (1951) made a similar calculation (numerical values unpublished) for the annular aperture. Defining the quantity P as the ratio of the energy in the central disk to the total energy, one obtains

$$P = \int_0^{r'} I r dr / \int_0^\infty I r dr. \quad (2)$$

The limits on the numerator integral are such as to include only the central disk. The corresponding limit on r , namely r' , is a function of α and corresponds to the radius of the first dark ring. The numerator integral has been evaluated by numerical integration for each value of α . The denominator integral may be evaluated exactly, since the definite integrals which arise are known (Watson 1944). The resulting values of P are given in Table I. The values of r' are also tabulated and these decrease as α increases. Although r' is the radius of the first dark ring, it is also very nearly a constant multiple of the

apparent diameter of the central disk. A slight decrease in size of the central disk as α increases is evident.

TABLE I.

α	γ'	P	C
0	3.832	0.838	5.17
0.05	3.820	0.832	4.95
0.10	3.786	0.818	4.49
0.15	3.733	0.795	3.88
0.20	3.665	0.764	3.24
0.25	3.586	0.732	2.73
0.30	3.501	0.682	2.14
0.40	3.323	0.584	1.40
0.50	3.144	0.479	0.92
0.75	2.739	0.219	0.28

It is suggested here that the contrast between the central disk and the rings can best be described by a factor C defined by

$$C = P/(1 - P), \quad (3)$$

giving the ratio of the energy within the central disk to the energy outside the central disk. The values of C are given in Table I and plotted as the solid line on Figure 3 where it is seen how rapidly this contrast factor drops as α increases.

A common criterion for image quality is that based on the Rayleigh tolerance and this permits a reduction in intensity at the center of the pattern of about 22 per cent compared to the ideal pattern. (The total energy of the pattern is held constant.) Marechal (1949) has shown that the precise percentage reduction tolerable depends on which aberration is under study. Grey (1951) has applied this tolerance to the annular aperture in connection with a detailed study of reflecting microscopes. In the absence of other aberrations the 22 per cent reduction in central intensity occurs when α is 0.47 and the corresponding value of contrast factor C is found to be unity. Thus for values of C extending above unity to the maximum value of 5.17 we are dealing with image quality requirements more stringent than the Rayleigh tolerance.

c. *Discussion.* The central obstruction blocks out some of the light and the whole pattern is less intense than it would have been otherwise, but this has been allowed for in the calculation of P . This loss in overall intensity is of minor importance compared to the diffraction effects.

The increased intensity of light in the rings outside the central disk as α increases would lead one to expect an undesirable loss in contrast. On the other hand the decrease in size of the central disk would suggest an improvement in resolving

power despite this loss of contrast. It is interesting to inquire which of these considerations is most important in actual observing practice.

Lord Rayleigh (1872) called attention to the theoretical increase in resolving power with large central obstructions and this well known prediction has been discussed recently by Osterberg (1949). The experiments of Dall (1938) indeed show a perceptible improvement for the obstructed aperture, but only for the special case of double stars of equal intensity. These stars have sensibly smaller disks and are more clearly separated than they are when the clear aperture is used.

However, Dall's experiments show that a marked loss of contrast does indeed occur with attendant practical deterioration in definition when the obstructed aperture is used on double stars of unequal intensity or on simulated planetary and lunar detail. This conclusion is supported by the experience of Pickering (1930) and other observers of planetary detail.

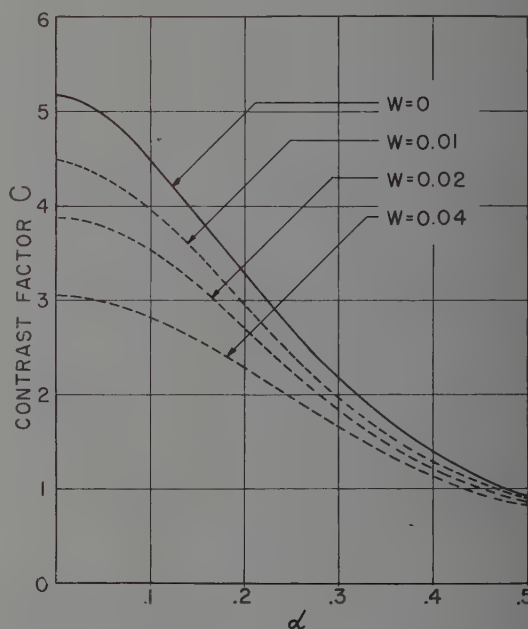


Figure 3. The contrast factor C , defined as the ratio of the energy within the central disk to the energy outside the central disk, is plotted as a function of α , the ratio between the diameter of the central disk and the aperture diameter. The solid line gives this function where there are no supporting struts, and the dashed lines give the value of C when there are four supporting struts of various widths. The parameter W is the ratio of the width of the strut to the aperture.

Those who have actually tried to separate close double stars with a telescope know that they rarely appear as two clean-cut overlapping diffraction patterns. The central disks are in evidence, but the seeing is rarely good enough for the ring patterns to be seen clearly. The light in the ring structure contributes to a surrounding glow and causes a loss in contrast where it is often difficult to see the fainter star.

For these reasons the criterion is adopted here that the definition is markedly improved, under practical conditions and for most purposes, as the contrast factor C increases. The clear unobstructed aperture, as in a refractor or an off-axis reflector, is then the best. If a secondary

mirror is necessary, it should be kept as small as possible.

Of course the secondary mirror cannot be made arbitrarily small if it is to accept the full cone of light from the primary mirror for all objects in the desired image plane. Generally speaking, Cassegrainian and short focus Newtonian telescopes will require relatively large secondary mirrors—between 0.33 and 0.25 times the aperture. A Newtonian design of $f/8$ to $f/12$ proportions can use a smaller secondary mirror, perhaps 0.20 to 0.15 times the aperture. Certain special systems [Johnson (1944), Dall (1952) and Thornton (1950)] require even smaller secondary mirrors, no larger than 0.10 times the aperture. Designs

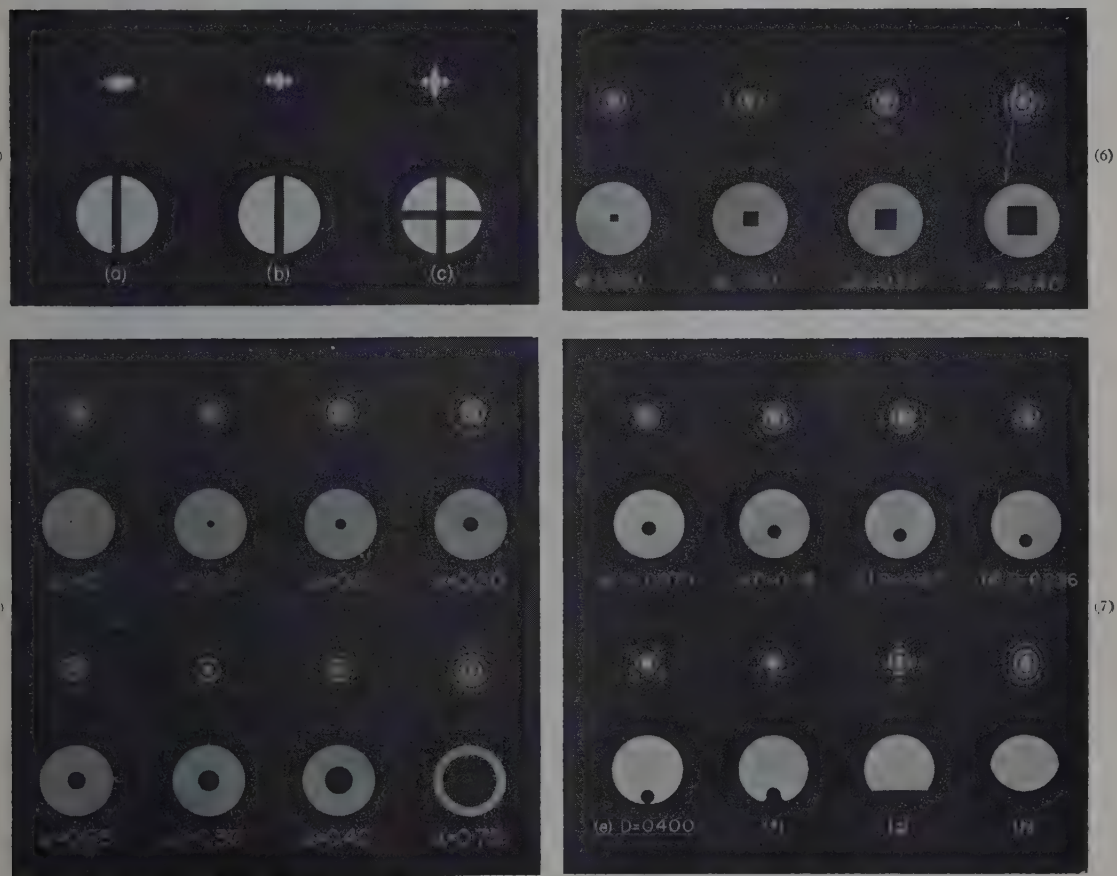


Figure 4. Diffraction patterns obtained by placing a bar-shaped obstruction in turn a full focal length in front of the mirror and then adjacent to the mirror.

Figure 5. Diffraction patterns obtained for annular apertures of various obstruction ratios α .

Figure 6. Diffraction patterns obtained for apertures with square central obstructions of various obstruction ratios α .

Figure 7. Diffraction patterns obtained for various off-center obstructions. Here D is the ratio of the off-center distance to the aperture. The obstruction ratio α is 0.2 in the first five cases.

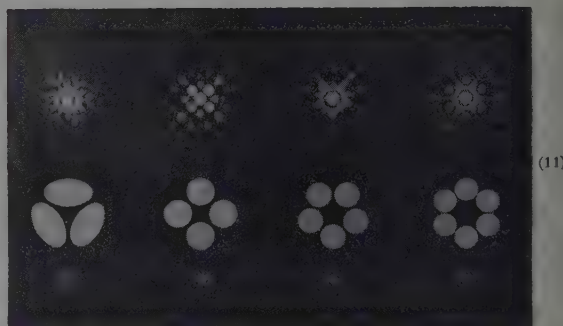


Figure 8. Diffraction patterns obtained for 0.2 diameter central stop supported by four struts of various widths.

Here W is the ratio of the width of the strut to the aperture.

Figure 9. Diffraction patterns obtained for a 0.2 diameter central stop with a single supporting strut and with three supporting struts. Here W is the ratio of the width of the strut to the aperture.

Figure 10. Diffraction patterns obtained for various unsymmetrical arrangements of straight struts supporting a 0.2 diameter central stop. Here W is the ratio of the width of the strut to the aperture.

Figure 11. Diffraction patterns obtained for arrangements of 3, 4, 5, and 6 oval or circular holes.

Figure 12. Diffraction patterns obtained for a various curved strut supporting a 0.2 diameter central stop. Here the ratio of the width of the strut to the aperture is 0.066.

for off-axis reflectors free of central obstruction have been reviewed by Ingalls (1954).

There is another factor which was not treated in our experiments, but which should be mentioned here since it is found to cause a further deterioration in definition. It is known that there

are persistent air currents in telescope tubes caused, in part, by temperature differences between the several parts of the telescopes and the surrounding air. These currents of air of differing temperatures and varying indices of refraction flowing over and around the secondary mirror

can contribute to poor definition. Practical discussions of these effects and suggested cures are given by Pickering (1930), Ingalls (1952), Hibbard (1944), Hargreaves (1949), and Rösche (1955). It may safely be said that making the secondary mirror smaller will make these effects less harmful.

5. SQUARE CENTRAL STOPS

Some small Newtonian telescopes use totally reflecting prisms in place of diagonal mirrors, and it was therefore of interest to study square obstructions. The resulting diffraction patterns are shown in Figure 6. In this series α is the ratio of the side of the square to the diameter of the aperture. The patterns are similar to those for the corresponding circular disks except that as the squares become larger the rings become segmented. The discussion of the preceding section applies generally to the square obstructions as well as to the circular obstructions.

6. OFF-CENTER OBSTRUCTIONS

A circular stop 0.2 the aperture of M was used in a series of measurements to determine the effect on the diffraction pattern caused by decentering the obstruction. This size was chosen because it is commonly used in Newtonian telescopes of moderate focal ratios.

There are two reasons for studying these off-center patterns. First, it is interesting to determine the tolerances on exact centering of the secondary mirror in so far as it affects the diffraction pattern. In fact, in a short focus Newtonian design as in Figure 1, the secondary mirror, if of minimum size, must be slightly decentered to accept the full cone of light. Secondly, a gross off-centering is a partial approach to a Hershelian or other off-axis design, and it is interesting to see whether an improvement in the pattern is to be found with the secondary mirror near the edge of the aperture.

The central stop was mounted on fine glass fibers on a movable frame and was located, in this case, in the collimated beam at a distance of three-quarters of a focal length from the telescope mirror M .

Figure 7 (a, b, c, d, e) shows the drawings of the diffraction patterns obtained in this way. The number beneath each drawing represents the ratio D of the off-center distance to the diameter of the aperture. For D equal to zero there would be no decentering. Changes begin to be evident

for D equal to 0.118 where the ring structure begins to segment. Further decentering causes the rings to become a series of arcs. For D equal to 0.400, where the edge of the circular stop is projected tangent with the edge of the aperture, the first bright ring is very much distorted. The second ring has become four arcs, and a confused pattern results with an elongation of the central disk.

The patterns of Figure 7 (e, f, g, h) were made to find out if additional masking (with an outline large enough to cover a secondary mirror tangent to the aperture) would improve the pattern.

7. MEANS OF SUPPORTING A SECONDARY MIRROR

a. *Four supporting struts.* It is well known that the struts which support the secondary mirror in reflecting telescopes cause spikes and other modification in the diffraction patterns. Comparative photographs and drawings were made of the patterns produced by four struts supporting a 0.20 diameter circular central stop.

The struts were made from wire of various diameters and arranged as shown in Figure 8 (a). The width of the strut is expressed by a quantity W , which is the ratio of the actual width to the aperture. Figure 8 (b) shows the diffraction pattern of a rather severe case, $W = 0.070$. The pattern consists of spikes which are quite prominent and the first bright ring has taken on the shape of a square. This value of W , corresponding to struts 0.700 inch wide in a ten inch aperture telescope, is considerably larger than would be found in a practical design. As W decreases to 0.032 the spikes become longer and less intense. For $W = 0.018$ the spikes are too long to show entirely on the drawing and are rather faint. For $W = 0.014$ and 0.010 the spikes were too faint to show on the original negatives, but when an eyepiece replaced the camera in the optical system long spikes were easily seen visually in these cases.

b. *Single supporting strut.* A series of photographs were taken of the diffraction patterns produced by a circular aperture with a 0.2 diameter circular central stop supported by a single strut. The resulting patterns, shown in Figure 9 (a, b, c) are comparatively simple. The two spikes are opposite one another, and are broader and fainter than in the corresponding four strut patterns.

c. *Three struts spaced symmetrically.* Three struts were spaced 120° apart supporting a 0.20

diameter central obstruction. The resulting patterns, shown in Figure 9 (d, e, f) have six spikes as expected. However, these spikes are unusual in that they appear to have a soft-textured structure, an overlapping between the maxima and minima within the spikes.

d. *Unusual forms of struts.* Many kinds of special supports have been suggested which modify or tend to eliminate the diffraction spikes.

Figure 10 (a) shows the pattern for two struts 90° apart. Here there is a resemblance to the four strut patterns of Figure 8. Figure 10 (b) shows two parallel struts extending from one side only, and this pattern may be compared with the single strut patterns of Figure 9 (a, b, c). Figure 10 (c), which shows two struts 120° apart, gives a pattern somewhat similar to the three strut patterns of Figure 9 (d, e, f).

Figure 11 contains a series of patterns for apertures consisting of 3, 4, 5, or 6 oval or circular holes. In each case there is sufficient opaque space at the center to hide a secondary mirror of 0.20 diameter or larger, and sufficient space between the holes to provide support. The aperture of Figure 11 (a) with three oval openings gives a pattern with a hexagonal first ring and some faint outer structure, but is surprisingly good considering the extent of the obstruction. The aperture of Figure 11 (b) with four circular openings gives an interesting pattern of dots which is far from a desirable pattern. The aperture of Figure 11 (c) with five holes yields a pattern with 10-fold structure and that of Figure 11 (d) with six holes yields a pattern of 6-fold symmetry.

Figure 12 shows the patterns resulting from several forms of curved supporting struts. It is seen that the spikes have disappeared and are replaced by a faint-textured overall pattern.

Couder (1952) has described a form of spider in which the four struts are spindle-shaped with an outline formed by arcs of circles. He finds that the spikes disappear from stellar images. The spindle shape which he describes was difficult to simulate on the small scale of our experiments and we did not test it. Any form of curved support would be expected to give spread-out patterns as in Figure 12.

e. *Discussion.* Any system of struts will scatter some energy from the central disk and cause loss in contrast. The extent to which this occurs with a four strut support has been computed. The calculation is straightforward and similar to that carried out in Section 4b above, but is rather too long to present in detail here. Having obtained

an exact expression for the diffracted field one integrates to find the fraction P of the energy in the central disk, and from this the contrast factor C is obtained. The results are shown as the dashed curves in Figure 3, where it is seen that the reduction in contrast may not be negligible even with struts of reasonable proportions. Thin struts, certainly no wider than 0.005 or 0.01 times the aperture, are to be recommended. Further detailed analysis of other strut systems shows, to a good approximation, that the energy scattered from the central disk by any strut system depends on the obstructing area of the struts and not on their detailed shape. Thus, for the same effect on the contrast factor, a single strut support may be four times as thick as each strut of a four strut system, and so on. This scattered energy appears as long narrow spikes in the four-strut case, as wider and more diffuse spikes in the three-strut case and as a complicated overall pattern when the struts are curved.

The loss in contrast caused by the struts can be completely avoided by mounting the secondary mirror on an optically-plane parallel glass plate the size of the aperture in a Newtonian design, or mounting it directly on the correcting lens as in certain catadioptric systems (Bouwers 1946, Maksutov 1944).

There is no one kind of supporting strut system which is best of all cases. The spikes can be eliminated by one of the several systems of curved struts. However, these curved supports are necessarily thicker than straight struts need be and will scatter a considerable amount of light outside the central disk and cause an unnecessary loss of contrast. Some may prefer the sharp narrow spikes of a four strut support, since these spikes are often useful in locating the precise position of bright stars. The writers' preference

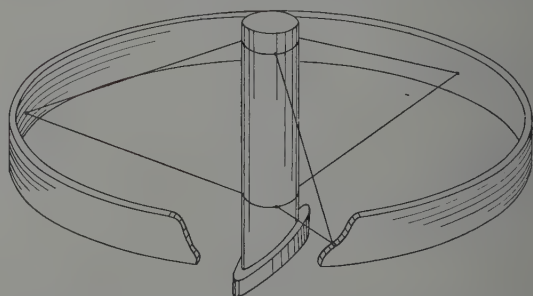


Fig. 13. A means of supporting the central mirror of a Newtonian telescope with six fine wires under tension. This illustrates one suggestion for minimizing the light scattered by the supporting struts.

is for a three strut support made of six fine wires under tension as in Figure 13. The wires can be so thin that the scattered light is almost negligible.

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PHOTOELECTRIC PHOTOMETRY OF COMET AREND-ROLAND (1956h)

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Abstract. Photoelectric observations of comet Arend-Roland were made on eleven nights in the blue, yellow and with an interference filter centered at 4065 Å. The intensity with the interference filter decreased less rapidly than in the blue and yellow for which agreement with the results of Thiessen were found. Intensity tracings across the comet could be adequately represented by the fountain model with a Maxwell-Boltzmann distribution for the ejection velocities.

The purpose of this paper is to provide photometric information on the behavior of the coma of Comet Arend-Roland. The explanation of the appearance of a comet is complicated by variation in the behavior of individual comets as well as by the differences in behavior of the various spectroscopic species contributing to the light of the comet. Only a limited amount of accurate photometric data is available to resolve these problems. An attempt to explain the observations with the help of the fountain model is partially successful.

Photoelectric observations made on ten nights during April and May 1957 are discussed. The instrument used was the ten-inch visual refractor of the observatory. A photoelectric photometer with a 1P21 photomultiplier was attached. The diaphragm diameter of 1.5 mm combined with a focal length of 172 inches for the telescope gives an angular diameter of 1'.18 for the diaphragm

projected onto the sky. The filters used were: yellow, Schott GG11; blue, Schott GG13 plus Corning 5030; an interference filter (IF) centered at 4065 Å. The transmission of the interference filter was determined with a spectrophotometer using an incandescent lamp as a light source and the resulting transmission curve is shown in Figure 1, where the peak transmission has been arbitrarily set as 100. Over the wavelength range covered by these filters appreciable errors in the quality of the image can be expected due to secondary spectrum (residual chromatic aberration) of the refractor. To minimize this effect, an intermediate focus was used which produced circles of confusion approximately 0'.3, 0'.4, and 0'.5 in diameter as projected on the sky for the blue, yellow and interference filter respectively. The output of the photomultiplier was amplified with a DC amplifier and recorded on a Brown recorder.

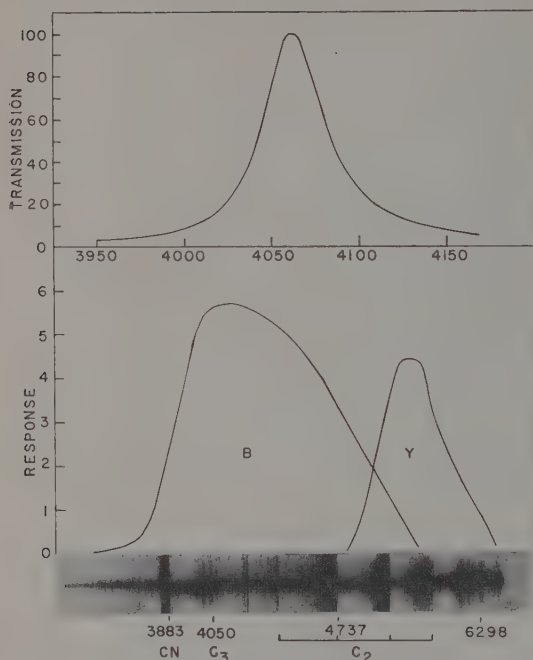


Figure 1. Top, the transmission of the interference filter relative to the peak value. Bottom, the relative response of a photometer for the blue and yellow compared with a spectrum of Comet Cunningham.

Two types of observations were obtained. First, the comet was centered in the diaphragm visually and the magnitude measured in each color. Second, the telescope was displaced in right ascension or declination and then traced over the comet in right ascension or declination to give an intensity profile of the comet in two directions. The rate of motion was $5'.92/\text{min}$ in declination and $6'.27 \cos \delta/\text{min}$ in hour angle. With the help of observations of comparison stars, the appropriate corrections for extinction were made.

The effect of extinction is large at the zenith distances for which the comet was observed and considerable uncertainty remains in the derived magnitudes. For broad band filters the correct extinction coefficient must remain quite uncertain. The distribution of intensity of the light from the comet, when it is near the sun, does not resemble that of the stars usually employed for determining the extinction coefficients. Figure 2 shows the spectral response for yellow and blue filters as given by Johnson and Morgan (1951) compared with a spectrum of Comet Cunningham as reproduced in the Atlas of Representative

Cometary Spectra. The effective wavelength for the blue magnitudes will be determined by the relative intensities of the CN, C₃ and the C₂ bands. For the yellow magnitudes the C₂ bands are mainly responsible for determining the intensity distribution. The observed colors of the comet are no simple indicator of the appropriate extinction coefficients to employ, although the presence of reflected solar light will reduce the discrepancy. An approximate indication of the effective wavelength may be obtained by using estimated intensities of the spectral features given in the Atlas of Representative Cometary Spectra with the response of the photometer to light of different wavelengths.

Of course these values will vary with the comet's distance from the sun and with the part of the comet being observed. This emphasizes the importance of using narrow pass band filters for the accurate photometry of comets. Because of these considerations, which introduce systematic errors in the magnitudes varying with

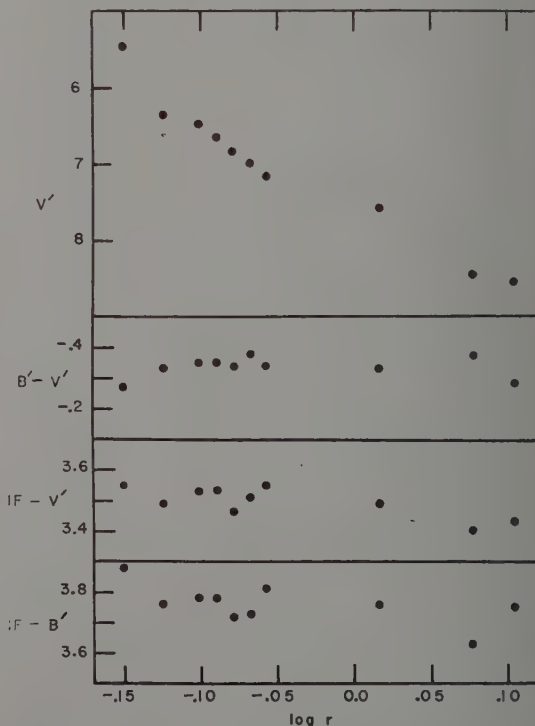


Figure 2. The colors and magnitudes of the center of the coma as a function of the distance from the sun. The observations refer to a fixed angular size, so that the area on the comet varies with the date.

the distance of the comet from the sun, and because of the limited accuracy of the data, the extinction coefficients appropriate for AO stars were adopted.

The observed magnitudes on the instrumental system for the blue, yellow and interference filter will be designated by B' , V' , and IF ; the zero point has been taken to give approximate agreement between the V and V' . For stars the following relations between the B' , V' , and IF and the B , V system of Johnson and Morgan were derived:

$$V = V' + .04(B' - V') + .03$$

$$B = B' + .32(B' - V') + 1.12$$

$$B - V = 1.28(B' - V') + 1.09$$

approximately:

$$IF - V' = 1.47(B - V) + 2.40$$

$$IF - B' = .69(B - V) + 3.25.$$

However, the transformation is a function not only of the instrumental systems but of the intensity distribution of the object being observed as well. Since the intensity distribution for the comet differs so markedly from that of the stars used in obtaining the above relations, no attempt was made to transfer the observed comet magnitudes and colors to the standard B , V system.

The magnitudes and colors observed for the comet are shown in Table I. Because of the nature of the observations no correction for the variation in distance between the earth and the comet has been applied. In general the change in size of the diaphragm as projected on the comet will tend to compensate for the change in distance; however since the intensity of the comet falls off with the distance from the center, the magnitudes obtained when the comet is more

distant will be fainter than if a constant area on the comet had been observed and corrected for the distance. Nevertheless, a plot of the observed magnitudes versus the logarithm of the distance from the sun, Figure 2, shows generally the same appearance as does that of Thiessen (1957). The values can be fitted by an approximately straight line with the value for May 1 falling somewhat high. Although this is the least reliable value here, it may be noted that Thiessen found a similar deviation at this time, which he indicated was related to solar activity.

The $B' - V'$ colors show little indication of variation over the interval covered by the observations. This is in general agreement with the result of Thiessen. The decrease in the color index observed by him is mainly determined by one point at a smaller value of r than covered by the present observations. The $IF - V'$ colors show a decrease with increasing r . This is an indication that the C_3 bands decreased in intensity less rapidly than did the C_2 bands, which are the principal contributors to the V' magnitudes. Of course, since the observations at different dates refer to different areas on the comet, the distribution of intensity over the comet should be considered; this will be discussed below.

Tracings through the head were obtained every night the comet was observed; however only four nights will be discussed here. These tracings are affected not only by the limited resolution but also by the time constant of the photometer. The response of the Brown recorder is sufficiently fast that its contribution to the shape of the tracing may be neglected. The response of the entire system was checked by observing stars and by flashing an artificial light source on the photomultiplier. A time constant of 0.8 second was determined, in agreement with the value expected from the resistance and capacitance at the input to the amplifier. With the observed

TABLE I. MAGNITUDES AND COLORS

Date	Δ	r	V'	$B' - V'$	$IF - V'$	Equivalent diaphragm diameter in 10^4 km
May 1.11	.742	.707	5.46	-.33	3.88	3.81
3.10	.798	.750	6.36	-.27	3.76	4.10
5.10	.856	.792	6.48	-.25	3.78	4.39
6.11	.886	.813	6.65	-.25	3.78	4.55
7.12	.917	.834	6.83	-.26	3.72	4.71
8.12	.947	.855	6.99	-.22	3.73	4.86
9.12	.977	.876	7.15	-.26	3.81	5.01
17.12	1.223	1.038	7.58	-.27	3.76	6.28
25.13	1.463	1.195	8.44	-.23	3.63	7.51
29.14	1.579	1.270	8.55	-.32	3.75	8.10

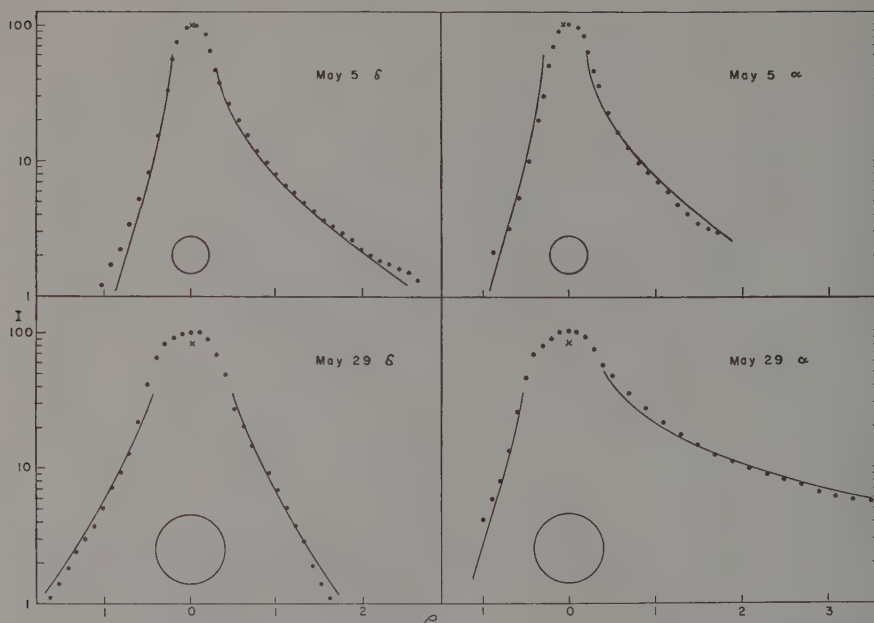


Figure 3. Intensity profiles through the nucleus of the comet; the abscissa is in units of 100,000 km. The large circles give the size of the diaphragm as projected on the comet. The dots are observed values corrected for the time constant of the photometer. The solid curves and the crosses represent the profiles predicted by the fountain model.

shapes of the curves the corrections for this effect amount to only a few percent of the observed values over most of the curves. Corrections were applied by numerically determining the rate of change of the deflection at close intervals.

Near the nucleus of the comet, the intensity changes rapidly over small distances so that the secondary spectrum and the large size of the diaphragm make it difficult to obtain the true intensity profile of the comet. However, in the outer regions this problem is much less serious. Figures 3 and 4 show several observed intensity profiles. In most cases, the variation of intensity with distance can be approximately represented on a logarithmic scale by a straight line in the outer regions of the comet, corresponding to an exponential decrease of intensity with distance.

Attempts were made to reproduce the observed intensity distributions with the fountain model employing a dispersion in the ejection velocities of the particles emitted by the nucleus. A discussion of phenomenological models of comets is given by Wallace and Miller (1958) and the relevant formulae are taken from their article. The intensity distribution was computed numer-

ically from the formula

$$N = \frac{\pi}{\rho} \int_{g_1}^{g_2} \frac{n(g)}{g} dg,$$

where $g_1 = \sqrt{a\rho} \sqrt{1 - \cos \theta}$, ρ and θ are polar coordinates in the plane of the sky with origin at the nucleus and $\theta = 0$ in the anti-solar direction, a is the acceleration in the anti-solar direction, $n(g)$ is the number of particles emitted with velocity g . Initially $n(g)$ was taken to be a Gaussian distribution. The value of the integral was determined numerically for several different values of the parameters, with g_2 taken at a convenient value for which no further significant contributions to the integral were to be expected.

In the region $45^\circ < \theta < 315^\circ$ and away from the nucleus the intensity can be represented approximately as decreasing exponentially with the distance ρ . This is in agreement with the observational results. When $1/\rho$ is small the value of $D = \frac{d \log N}{d \rho}$ is given by the derivative of the integral. Then, since the distance at which g_1 is attained is given by $\rho_1 = g_1^2/a(1 - \cos \theta)$ the ratio of the derivatives for two values of θ

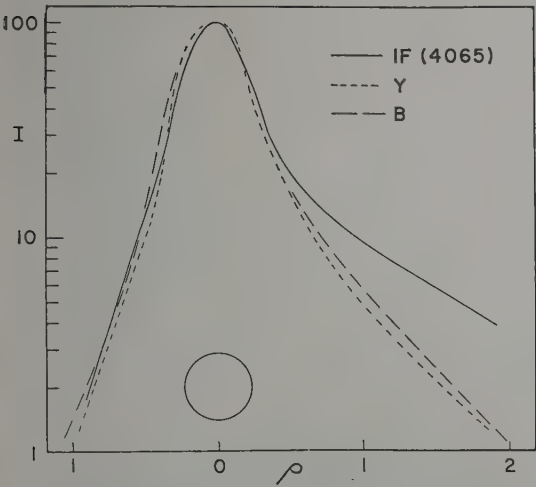


Figure 4. Intensity tracings in declination through the nucleus in three colors on May 7.

will be given by $(1 - \cos \theta_1)/(1 - \cos \theta_2)$ or for two values of θ differing by 180° as in the observations by $(1 - \cos \theta)/(1 + \cos \theta)$ for a single tracing in right ascension or declination. The observed slopes may easily be corrected for the effect of the diaphragm size if it is assumed that within the diaphragm the intensity may be represented by an exponential decrease in one dimension and is constant at right angles to that direction. When the observed and predicted ratios of slopes are compared, the agreement is poor, the observations showing more nearly equal slopes than predicted.

A simpler comparison is possible if $n(g)$ is taken as the Maxwell-Boltzmann distribution:

$$n(g) = Ag^2e^{-\lambda g^2}.$$

Then the value of $\dot{N}$ may be computed from the integral in a closed form as

$$N = \frac{B}{\rho} e^{-\lambda a \rho (1 - \cos \theta)}.$$

While the expression for the derivative D will show the same ratio as that derived earlier, when $1/\rho$ is negligible, this formula has the advantage of simplicity in fitting the observations when $1/\rho$ is not negligible, as is the case here, and employs a physically plausible velocity distribution. When the line of sight is not perpendicular to the line joining the sun and the comet, the expressions

for g_1 must be modified. This can be accomplished by projecting onto the plane of the sky the paraboloidal envelope within which lie all trajectories for velocities of amount g_1 or less. The expressions for g_1 and N become

$$g_1 = \sqrt{a\rho \sin \varphi} \sqrt{1 - \cos \theta}$$
$$N = B \frac{1}{\rho} e^{-g_1^2},$$

where φ is the angle between the line of sight and the line joining the sun and comet.

This expression has been fitted to the observations for two nights in the blue and the resulting agreement is shown in Figure 3. The effect of integrating the light of the comet over the size of the diaphragm was introduced into the theoretical curves by numerically integrating the intensity N over the size of the diaphragm. It was assumed for this purpose that within the area covered by the diaphragm, the intensity varied only with x , the rectangular coordinate coinciding in direction with ρ at the center of the diaphragm. This assumption is poor when near the nucleus so the theoretical curves were not carried all the way in. With the diaphragm centered on the nucleus the predicted intensity can be readily obtained by expanding the exponential and integrating over the area in polar coordinates. These values, which lie on the theoretical curves, are shown by crosses in Figure 3. The infinite intensity predicted by the expression for N when $\rho = 0$, occurs because the size of the nucleus has been neglected. This does not introduce any difficulty since the discontinuity is removed on integrating over the area. The parameters of the curves are given in Table II.

TABLE II. PARAMETERS OF THE FOUNTAIN MODEL

Date	$\lambda a \sin \varphi \times 10^3 \text{ km}^{-1}$			Observed θ			Computed	
	V'	B'	IF	V'	B'	IF	θ	φ
May 5.1	2.7	1.8	1.0	49	47		38	75
7.1	2.0	2.1	1.6		55	23:	41	72
25.1	3.2:	2.2		75	73		63	43
29.1	2.1	1.4	1	80	90		64	39

The values of θ used deviate somewhat from those predicted by the relative positions of the sun, comet and earth because of the actual procedure used in obtaining the parameters. The values used deviate in the same sense and by about the same amount as was found from photographic observations by Wenske (1958). Further

adjustment might result in a better fit, but this did not appear to be justified in this case with the large size of the diaphragm and the other sources of uncertainty present.

The individual values of a and λ cannot be determined, only their product can be obtained here. Since the parameters available with this model to fit the observations are λa , B and the location of the maximum intensity, corresponding to a horizontal displacement, the agreement appears to indicate a satisfactory approximation to the comet. No attempt was made to include the effect of decay of the molecules emitting the light.

The differences between the tracings with different filters are shown for one night in Figure 4. The deviation of the IF tracing from the B' and V' reaches about three units on the intensity scale and is larger than in any other tracing considered. It is probably not significant because the highest sensitivity setting of the amplifier was required for this tracing and the noise could

introduce uncertainties of the order of one or two units. The close agreement of the yellow and blue tracings is generally typical of the other tracings. The blue tracings seem to be slightly broader than the yellow. This effect was also reported by Lodén in the data of Bouique (1958). Our results show that on May 5 the blue was about one unit higher than the yellow at the ends of the tracings; by May 29 the discrepancy was scarcely detectable. No comparison with the IF was possible at this time since the comet was too faint to obtain a tracing.

The financial support of this work by the National Research Council of Canada is gratefully acknowledged.

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NEW LIGHT ELEMENTS OF FIVE ECLIPSING VARIABLES

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Abstract. During the winter of 1958-1959, the times of minimum of five eclipsing variables, TV Cassiopeiae, XX Cassiopeiae, BX Andromedae, WW Aurigae and W Ursae Majoris, were observed photoelectrically. From the observational data, new light elements for these variables were derived.

Introduction. The telescope employed was the 15-inch horizontal refractor with a 25-inch siderostat. This was equipped with the Newton Lacy Pierce photometer (Blitzstein 1956), using a multiplier photocell RCA IP21. For all observations the filter used was Corning No. 3384, 1.75 mm thickness, the effective wave length of the photocell-filter combination being 5150 Å. All observations are reduced to heliocentric time. In order to obtain the time of minimum, both Hertzprung's method and Miss Szafraniec's tracing paper method were used in each case.

TV Cassiopeiae. TV Cassiopeiae is BD +58° 30(7^m3), HD 1486; spectral class B9. The variability of the system was discovered by Astbury (1911). He announced that it was an Algol type with period 1^d8126. Since this time, it has been frequently observed, and at least 74 times of minimum have been published.

The variable was observed by the author on

two nights. One time of minimum was obtained at JD 2436483.8091. The comparison star used was BD +58°24 (7^m4). Since there exist few observed times of minimum light between 1914 and 1939, it is rather difficult to picture the exact behavior of the period. However, it seems probable that there was one period change from 1^d81260009 to 1^d81261301 around 1935, and since then the period has remained constant. Due to the complex distribution of the residuals, the improvement of the period was made using only the data of the last 30 years. The new light elements derived from this data are thus:

Hel. Min. I = JD 2436483.8091 + 1^d81261301 *E*.

XX Cassiopeiae. XX Cassiopeiae is BD +60° 246 (9^m2), HV 3550; spectral classes as given by Wyse are B4n, B6n. Mackie (Bailey 1921) first discovered the variability of this star photographically. Studies of the light elements to 1938 have been summarized by Pierce (1938).

TV CASSIOPEIAE

JD Hel 2436000+	Δm	JD Hel 2436000+	Δm	JD Hel 2436000+	Δm	JD Hel 2436000+	Δm	JD Hel 2436000+	Δm
477.5936	-.413	483.5974	.378	483.6614	.309	483.7238	-.049	483.7950	-.607
.6104	-.270	.5982	.375	.6646	.290	.7246	-.044	.7990	-.626
.6136	-.241	.6014	.356	.6654	.313	.7286	-.060	.7998	-.610
.6168	-.179	.6022	.359	.6686	.277	.7342	-.122	.8030	-.624
.6216	-.152	.6062	.379	.6694	.284	.7438	-.205	.8038	-.627
.6248	-.181	.6070	.381	.6726	.276	.7446	-.216	.8078	-.619
.6528	.088	.6142	.368	.6734	.278	.7486	-.224	.8086	-.617
.6560	.106	.6190	.375	.6766	.272	.7494	-.243	.8126	-.623
.6592	.117	.6198	.353	.6774	.246	.7526	-.267	.8134	-.631
.6624	.151	.6246	.384	.6822	.249	.7534	-.273	.8142	-.638
.6656	.143	.6254	.371	.6830	.232	.7566	-.312	.8182	-.591
.6728	.315	.6286	.387	.6910	.221	.7574	-.334	.8190	-.605
483.5542	.389	.6294	.373	.6926	.201	.7606	-.337	.8198	-.615
.5582	.359	.6342	.397	.6974	.178	.7614	-.335	.8230	-.609
.5590	.374	.6382	.355	.6982	.175	.7646	-.403	.8238	-.616
.5954	.357	.6390	.357	.7022	.157	.7654	-.419	.8246	-.623
.5662	.376	.6422	.363	.7038	.137	.7694	-.424	.8278	-.543
.5694	.378	.6430	.356	.7070	.095	.7702	-.428	.8286	-.553
.5702	.383	.6462	.347	.7078	.086	.7750	-.469	.8294	-.542
.5750	.360	.6470	.355	.7110	.075	.7798	-.507	.8342	-.529
.5758	.369	.6510	.341	.7118	.053	.7806	-.499	.8350	-.504
.5798	.365	.6518	.327	.7158	.027	.7854	-.509	.8358	-.502
.5806	.358	.6566	.337	.7166	.037	.7862	-.508	.8390	-.485
.5926	.373	.6574	.339	.7198	-.033	.7894	-.573	.8398	-.476
.5934	.379	.6606	.333	.7206	-.029	.7902	-.570	.8406	-.469
						.7934	-.613	.8454	-.449

XX CASSIOPEIAE

JD Hel 2436000+	Δm	JD Hel 2436000+	Δm	JD Hel 2436000+	Δm	JD Hel 2436000+	Δm	JD Hel 2436000+	Δm
527.4978	.373	527.5434	.188	527.5818	-.019	527.6186	-.044	527.6738	.141
.4986	.379	.5466	.191	.5850	.010	.6194	-.022	.6746	.149
.5018	.354	.5474	.164	.5866	.000	.6202	-.035	.6786	.208
.5026	.376	.5506	.166	.5893	.008	.6234	-.060	.6794	.186
.5066	.373	.5514	.137	.5906	-.016	.6242	-.065	.7002	.314
.5082	.336	.5546	.146	.5946	-.005	.6250	-.015	.7010	.349
.5122	.333	.5554	.138	.5954	-.013	.6316	.005	.7042	.358
.5130	.318	.5594	.078	.5962	-.001	.6354	-.033	.7050	.356
.5170	.301	.5602	.089	.5994	.002	.6362	-.021	.7090	.354
.5178	.320	.5634	.078	.6002	.005	.6370	-.008	.7098	.384
.5226	.293	.5642	.061	.6010	-.018	.6506	.021	.7138	.392
.5234	.278	.5674	.067	.6050	-.027	.6514	.004	.7146	.407
.5274	.285	.5682	.048	.6066	-.031	.6554	.000	.7178	.436
.5282	.263	.5714	.050	.6074	.007	.6562	.004	.7186	.433
.5314	.265	.5722	.033	.6114	.015	.6586	-.007	.7218	.452
.5322	.248	.5754	.047	.6122	-.044	.6594	-.018	.7226	.447
.5354	.210	.5762	.000	.6130	-.040	.6602	.021	.7282	.491
.5362	.194	.5770	.001	.6138	-.050	.6634	.016	.7290	.490
.5426	.187	.5810	.021	.6170	-.047	.6642	.025		

For the first time, photoelectric observations of this system were made by the author. The comparison star was BD +60°244 (9^m5). One time of minimum was obtained at JD 2436527.619. The new light elements derived from the observations are:

Hel. Min. I = JD 2436527.619 + 3^d0671773 *E*.

These observations confirm Pierce's conclusion that there is no evidence of a period change since the discovery of the system.

BX Andromedae. *BX Andromedae* is BD +40° 4421 (8^m5), HD 13078, SVS 995, spectral class

Go. The variability was discovered by Soloviev (1945). Ashbrook (1951, 1952, 1953) confirmed the variability by an examination of Harvard patrol plates. Svolopoulos (1957) made two-color observations photoelectrically.

The author observed the variable for two nights, and obtained two times of minimum at JD 2436528.7777 and 6538.540. The comparison star used is not listed in the BD chart. According to the author's estimate, the position of the comparison star is $\alpha = 01^{\text{h}}59^{\text{m}}15^{\text{s}}$ and $\delta = 40^{\circ}09'$ as of 1900.

BX ANDROMEDAE

JD Hel 2436000+	Δm	JD Hel 2436000+	Δm	JD Hel 2436000+	Δm	JD Hel 2436000+	Δm	JD Hel 2436000+	Δm
528.7370	1.149	528.7706	.895	528.7986	.986	.5336	.887	538.5688	1.047
.7410	1.120	.7714	.886	.7994	.993	.5376	.892	.5728	1.074
.7418	1.092	.7746	.889	.8034	1.010	.5384	.895	.5736	1.091
.7450	1.091	.7762	.867	.8042	1.008	.5400	.901	.5768	1.115
.7458	1.094	.7810	.879	.8050	1.020	.5424	.907	.5776	1.129
.7498	1.051	.7818	.887	.8082	1.049	.5432	.906	.5816	1.147
.7506	1.027	.7826	.890	.8098	1.094	.5488	.908	.5824	1.157
.7554	.990	.7858	.896	.8106	1.096	.5496	.913	.5864	1.180
.7562	.971	.7866	.924	.8146	1.110	.5552	.945	.5872	1.189
.7594	.987	.7474	.910	.8154	1.120	.5560	.947	.5904	1.213
.7602	.965	.7882	.917	538.5256	.959	.5600	.974	.5912	1.216
.7610	.961	.7922	.948	.5264	.959	.5608	.986	.5952	1.246
.7642	.955	.7930	.979	.5272	.957	.5640	1.019	.5960	1.252
.7650	.961	.7938	.974	.5320	.895	.5648	1.032	.5992	1.267
.7658	.921	.7946	.976	.5328	.882	.5680	1.038	.6000	1.259
.7698	.904	.7978	.988						

WW AURIGAE

JD Hel 2436000+	Δm	JD Hel 2436000+	Δm	JD Hel 2436000+	Δm	JD Hel 2436000+	Δm	JD Hel 2436000+	Δm
586.6004	.743	586.6308	.749	592.6350	.946	592.6638	.698	592.6878	.733
.6012	.736	.6348	.763	.6358	.934	.6670	.690	.6910	.785
.6020	.751	.6356	.770	.6390	.917	.6678	.672	.6918	.768
.6060	.709	.6364	.771	.6398	.901	.6694	.638	.6926	.818
.6068	.715	.6404	.791	.6406	.881	.6702	.675	.6966	.840
.6076	.705	.6412	.812	.6446	.835	.6742	.706	.6974	.831
.6124	.696	.6420	.811	.6454	.821	.6750	.708	.6982	.834
.6132	.694	.6460	.837	.6462	.824	.6758	.672	.7014	.870
.6140	.688	.6468	.855	.6494	.817	.6766	.683	.7022	.895
.6188	.693	.6516	.906	.6502	.776	.6798	.675	.7030	.904
.6196	.694	.6532	.925	.6510	.768	.6806	.676	.7070	.942
.6204	.693	.6572	.968	.6518	.773	.6814	.676	.7078	.962
.6228	.705	.6580	.964	.6550	.755	.6822	.677	.7086	.972
.6236	.728	.6588	.977	.6558	.755	.6854	.690	.7110	1.002
.6244	.714	.6628	1.025	.6614	.690	.6862	.713	.7118	1.032
.6292	.737	592.6334	.952	.6622	.694	.6870	.700	.7126	1.042
.6300	.741	.6342	.941	.6630	.679				

W URSAE MAJORIS

JD Hel 2436000+	Δm	JD Hel 2436000+	Δm	JD Hel 2436000+	Δm	JD Hel 2436000+	Δm	JD Hel 2436000+	Δm
574.6727	.564	574.7127	.917	574.7583	1.187	611.6806	.954	611.7318	.671
.6735	.540	.7167	.973	.7591	1.177	.6814	.932	.7326	.722
.6743	.536	.7199	1.019	.7599	1.195	.6822	.942	.7334	.716
.6783	.505	.7215	1.024	.7607	1.188	.6762	.909	.7382	.816
.6791	.508	.7223	1.041	.7458	1.147	.6770	.882	.7398	.814
.6799	.501	.7231	1.034	.9466	1.159	.6778	.887	.7406	.825
.6831	.502	.7271	1.055	.9474	1.143	.6918	.847	.7446	.892
.6839	.500	.7279	1.066	.9514	1.136	.6926	.843	.7454	.905
.6855	.505	.7287	1.070	.9538	1.136	.6934	.832	.7362	.909
.6887	.512	.7343	1.104	.9570	1.113	.6974	.759	.7510	1.018
.6895	.515	.7351	1.099	.9578	1.116	.6982	.738	.7518	1.013
.6903	.533	.7367	1.102	.9586	1.096	.6990	.712	.7526	1.028
.6943	.607	.7407	1.135	.9594	1.098	.7038	.616	.7558	1.048
.6951	.611	.7415	1.127	.9602	1.099	.7046	.599	.7566	1.075
.6959	.618	.7423	1.132	.9642	1.032	.7086	.535	.7574	1.063
.6991	.682	.7431	1.154	.9650	1.019	.7094	.527	.7614	1.106
.6999	.695	.7463	1.157	.9658	.998	.7102	.552	.7622	1.115
.7007	.716	.7471	1.158	.9666	.990	.7142	.546	.7630	1.113
.7047	.786	.7479	1.155	.9698	.991	.7150	.533	.7662	1.144
.7055	.815	.7487	1.152	.9706	.964	.7158	.519	.7670	1.133
.7063	.826	.7519	1.170	.9714	.947	.7190	.524	.7678	1.138
.7071	.837	.7527	1.174	.9754	.854	.7206	.543	.7718	1.165
.7111	.893	.7535	1.176	.9762	.815	.7254	.565	.7726	1.139
.7119	.911	.7543	1.176	.9770	.798	.7262	.576	.7750	1.135

Svolopoulos' light elements are well determined, but the new observations make a slight improvement possible. The new elements are: Hel. Min. I = JD 2436528.7777 + 0^d61011534 *E*. From the distribution of residuals of earlier observations plotted against epoch, it seems probable that this variable has shown a period change from 0^d61011222 to 0^d61011534 around 1952.

WW Aurigae. *WW Aurigae* is BD +32°1324 (5^m8), HD 46052; the spectral class is A7 for both components. Variability was discovered by Soloviev (1916) and independently by Schwab (1918). Many observers have studied the light elements.

The author obtained two times of minimum at JD 2436586.616 and 6591.6714. The comparison star was BD +32°1320 (6^m8). The residuals of photoelectrical observations presented by five observers, Piotrowski and Strzalkowski, Huffer and Kopal and Chou, were well distributed with small scatter. The new light elements were derived using only these photoelectric observations. They are:

Hel. Min. I = JD 2436591.6714 + 2^d5250214 *E*. The photoelectric observations indicate that there was no appreciable period change during the past 17 years. However, it seems probable that at least one period change took place around 1942, from 2^d5250184 to 2^d5250214. The brightness at

the bottom of primary differed by about 0^m02 on the two nights.

W Ursae Majoris. The short-period eclipsing variable, *W Ursae Majoris* is BD +56°1400 (7^m5), HD 83950, ADS 7494; spectral class is F8p. The variability of this system was discovered by Müller and Kempf (1903). Most of the observational data of earlier observers until 1942 were well summarized by Woodward (1942). Kwee (1956) reported that there seems to have been a rather abrupt change of the period. He suggested that the light curve may be slightly variable from cycle to cycle. The recent data were well summarized by Schmidt and Schrick (1956).

Two times of minimum were obtained from three nights' observations by the author. The comparison star used was BD +56°1399 (8^m5). Altogether, 134 observed times of minimum were used in this study. However, improvement of the period is not a simple problem, as illustrated by a plot of the residuals (Fig. 1). The author's best observed time of minimum is JD 2436611.7163.

The author suggests that the period 0^d3336384 probably would furnish better predicted times of minimum for later observations. However, he does not claim that the new period suggested will stand for any definite duration.

The system is well known for variation of period. Even with the recent data, it is still

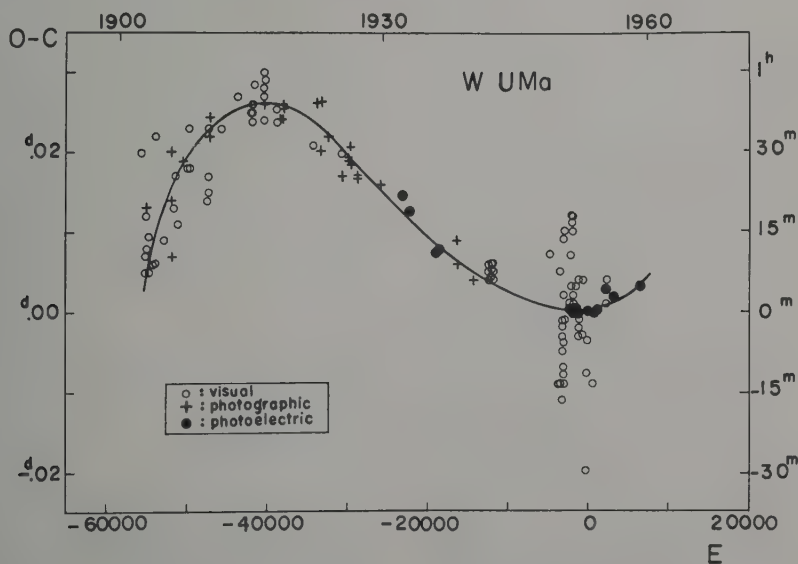


Figure 1. Residuals of observed minima for *W UMa*, computed from JD Hel 2434489.44286 + 0^d33363779 *E*.

difficult to tell whether the variation is cyclic or not. There may be short term periodic or irregular oscillations superimposed on a long term variation.

In the two minima observed, the brightness at the bottom of primary minimum was found to differ by about $0^m.02$.

Acknowledgments. The author wishes to express his hearty gratitude to Dr. Frank Bradshaw Wood, whose generous help made this paper possible. Appreciation is also extended to all faculty members of the Astronomy Department, University of Pennsylvania, who gave valuable suggestions and advice.

This work was submitted in partial fulfillment of the requirements for the master's degree.

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FURTHER REPORTS OF OBSERVATORIES

Goethe Link Observatory, Indiana University, Bloomington, Indiana.

Personnel. Dr. Goethe Link (Honorary Director), Professors Frank K. Edmondson (Director) and John B. Irwin, Associate Professor James Cuffey (Assistant Director), and Instructor Richard L. Sears comprised the resident academic staff. In addition, Dr. W. W. Morgan was Visiting Professor during four weeks in April and May.

Associate Professor Marshal H. Wrubel was on sabbatical leave and spent the year at the Max Planck Institut für Physik und Astrophysik in Munich. Dr. Sears took his place during this period. Research Associate A. M. J. Gehrels was in residence at the McDonald Observatory.

Mrs. Beryl H. Potter and Mrs. Delores J. Owings were full-time Research Assistants, and Mrs. Sharron Funkhouser served as Secretary.

The following students were part-time teaching and research assistants: James R. Carstens, William H. E. Day, John H. Evans, David Fischel, Choko Fujita, Robert D. Furber, Elizabeth Lynn Hallgren, Laura J. Houser, Arlo U. Landolt, James L. Neafus, R. C. Nigam, Louise S. Peters, Robert L. Pumfery, Robert E. Samuelson, Thomas M. Teska, and I. M. Winer.

Edward C. Olson held the Swain Fellowship, and also taught the elementary astronomy course at the Indianapolis Extension Center. James G. Peters was Assistant at the Research Computing

Center, and won the Sigma Xi Undergraduate Award. He was also elected to membership in Phi Beta Kappa. Donald C. Schmalberger held a National Science Foundation Pre-doctoral Fellowship.

Marion Todd continued as Instrument Maker, and James Orr as Caretaker at the Goethe Link Observatory.

Research. Cuffey continued his photometric work on a number of clusters, including NGC 7492, 6838, and 2158.

Edmondson completed the observing on his program of 11th magnitude A- and K-stars at the McDonald Observatory in January.

Gehrels supervised construction of a Wollaston polarization photometer by Mr. Todd and Mr. Teska. He used this at the McDonald Observatory to observe asteroids and the moon.

Irwin devoted most of his time to writing, and published a paper on "Standard Light-Time Curves."

Sears published his thesis "An Evolutionary Sequence of Solar Models," and used the IBM 650 at the Research Computing Center to extend this work to include recent results on revised nuclear reaction rates.

A number of students (Fujita, Landolt, Nigam, Pumfery, and Winer) undertook small observing programs with the 36-inch reflector.

Positions and magnitudes of 761 asteroids were published in the Minor Planet Circulars. All mag-

nitudes are now measured on the Cuffey iris photometer.

Landolt went to the Kitt Peak National Observatory on June 10 as the first Graduate Research Student to use these facilities. He planned to observe the light-curve of V382 Cyg with the 16-inch reflector.

Teaching. Enrollment in the elementary course was 130 in the first semester and 143 in the second. Summer session enrollment was 28. Advanced courses included: Navigation, Astronomical Photography, Introductory Astrophysics, Binary Stars, Eclipsing Binaries, Techniques of Astrophysics, Stellar Interiors, Interstellar Matter, Stellar Motions, and Seminar (problems of galactic structure and related extra-galactic problems).

Choko Fujita received the M. A., and James G. Peters received the A.B. with High Distinction.

Miscellaneous. Cuffey, Edmondson, Gehrels, and Wrubel attended the Moscow meeting of the International Astronomical Union. Mr. George F. Siddons, Indiana University electronics engineer, also attended. Edmondson attended the Radio Astronomy Symposium held in Paris just before the Moscow meeting. Sears received a travel grant from NSF to attend the 1959 Liege Symposium.

Edmondson and Irwin participated in the AAS-NSF Visiting Professors Program.

Three Public Nights were held at the Goethe Link Observatory, with lectures by Landolt, Edmondson, and Olson.

Colloquium speakers included the following visitors: Sandage, Margenau, Heeschen, Peery, Abt, Stock, Beer, Stoy, H. Wood and Nemiro. Other visitors included: Strughold, Siple, Findlay, and Zverev.

FRANK K. EDMONDSON, *Director*

Yerkes Observatory, University of Chicago, Williams Bay, Wis.

McDonald Observatory, University of Texas, Fort Davis, Texas.

This Report covers the biennium 1957-59.

Personnel. Dr. B. Strömbergren resigned as director on September 1, 1957 to accept a professorship at the Institute for Advanced Study at Princeton. Dr. G. P. Kuiper was appointed his successor. Dr. A. Blaauw, Associate Director, resigned August 1, 1957 to become Director of the Kapteyn Astronomical Laboratory at Groningen. Dr. A. B. Meinel was appointed Director, Kitt Peak National Observatory, Tucson, Arizona on

February 1, 1958. Dr. D. L. Harris accepted a position at Northwestern University October 1, 1957; Dr. G. R. Burbidge joined the staff October 1, 1957 as Assistant Professor. Mrs. Burbidge first received a postdoctoral fellowship, was later appointed Research Associate. Dr. D. N. Limber joined the staff July 1 and Dr. R. F. Kraft September 1, 1958, both as Assistant Professor. Dr. J. W. Chamberlain was promoted to Associate Professor July 1, 1959. Drs. B. Strömbergren and A. Blaauw were appointed Research Associates and are continuing certain research projects.

Appointments at the University of Texas were as follows: Drs. F. N. Edmonds and E. J. Prouse were promoted to Associate Professor, September 1, 1958; Dr. G. Herbig of the Lick Observatory was visiting professor at the Observatories April-May 1959, and gave a series of lectures; Dr. J. Stock became Resident Astronomer at McDonald July 1, 1959.

Dr. Morgan was invited to participate in the Solvay Conference at Brussels on "The Structure and Evolution of the Universe" in the Spring of 1958. Drs. G. R. and E. M. Burbidge attended the Radio Astronomy Conference at Paris, July 1958. They, and Drs. Chamberlain, Hiltner, Kuiper, and Morgan attended the 10th General Assembly of the IAU at Moscow, August 1958. Dr. Morgan spent several months at the Lick and Mt. Wilson-Palomar Observatories as guest-investigator.

Dr. W. H. van den Bos, director-emeritus of the Union Observatory in South Africa, was appointed Research Associate for 18 months, starting May 1, 1957; Dr. L. Woltjer of Leiden was Research Associate for one year, starting Dec. 1, 1957; Dr. Archibald Brown of Sydney was appointed 6 months, starting Jan. 1, 1958; while Dr. A. Dollfus of Paris was appointed 2 months, starting July 1, 1957.

Research Associates on projects sponsored by NSF, ARDC, and ONR included: Mr. D. W. G. Arthur, Dr. A. Behr, Dr. D. L. Crawford, Dr. C. Y. Fan, Dr. J. H. Focas, Dr. T. Gehrels, Dr. R. Hardie, Mr. B. Iriarte, Mr. A. P. Lenham, Dr. W. H. Reid, Dr. F. E. Roach, Mr. J. W. Tapscott, Dr. L. Wallace, Mr. R. Weitbrecht, Mr. A. D. Williams, and Mr. E. A. Whitaker.

Observatory assistantships were held by Messrs. D. L. Crawford, Heiser, Pesch, and Sagan. Project assistantships were held by Messrs. F. Bisshopp, J. C. Brandt, E. Moore, P. Pesch, C. Smith, P. Vandervoort, J. Wright.

PhD degrees were awarded to Messrs. D. L. Crawford, E. Mendoza, and D. Schulte.

Visitors who gave colloquia included: Drs. J. H. Bretz, A. Dalgarno, R. Dalitz, D. Dewhirst, A. Dollfus, F. N. Edmonds, R. H. Hardie, G. Herbig, T. Houck, F. Hoyle, P. Meyer, M. Minnaert, G. Münch, K. F. Ogorodnikoff, E. Öpik, D. Osterbrock, T. L. Page, E. Parker, J. L. Pawsey, M. Schwarzschild, M. J. Seaton, E. Shoemaker, J. Stock, and G. Westerhout.

Facilities and Equipment. At the Yerkes Observatory the twin 12-inch refractor was dismantled and replaced by a modern 16-inch reflector constructed largely in our shops. Its tail piece was made to match that of the McDonald telescopes so that the instrument can be used, besides for pilot programs and student training, for testing of newly constructed attachments to the McDonald telescopes. Hiltner equipped it with a photoelectric photometer with offset guiding. Further, ten new offices were built, the laboratory subdivided and reorganized, and four darkrooms rebuilt and equipped. A Salzman enlarger and other large processing equipment was installed partly in connection with the Lunar Atlas project. The Library was reorganized and much excess material sent elsewhere or discarded. At McDonald an extensive building and modernization program was approved by the University of Texas. A cooperative agreement between the Universities of Chicago, Texas, and Chile was entered into for the construction and development of a mountain observatory in north-central Chile; a 60-inch reflector sponsored by ARDC will be the first major instrument. A site-testing program got underway in May 1959 under the supervision of Stock.

Hiltner, aided by P. Pesch and R. Miller, constructed a two-diaphragm, multi-color photometer to increase the effectiveness of the 82-inch in photometry of faint stars, such as in M13. The two diaphragms isolate sky and star plus sky while dichroic filters are used for selecting three wavelength regions, which requires six cells in all. Commercially available pulse amplifiers and scalers (Hammer Electronics Co.) were employed. The instrument has functioned satisfactorily.

Under the Auroral project, Wallace has in connection with the IGY program put into operation a scanning spectrometer. It scans the visible spectrum in a few seconds with several angstroms resolution. It is being used to study changes in the auroral spectrum over short time intervals and for investigation of the twilight glow. Under

the planetary and lunar projects a Bendix-Friez Lumicon was adapted for attachment to the 40- and 82-inch telescopes for a 6 months' test run. Further, Arthur and Whitaker made an 8 by 10 inch camera equipped with a set of shaped focal-plane shutters for lunar photography and a versatile binocular attachment for visual observation. Two accurately-shaped half spheres of 3 feet diameter were made for the production of "rectified" lunar photographs of limb areas.

Weitbrecht designed and produced a set of integrators and programmers that have been used in photometric programs. Gehrels and Teska constructed a two-diaphragm Wollaston photometer used for polarization studies, particularly of the moon and planets, in the region 3000–10,000Å. Abt modified the microphotometer so as to record intensities directly; and installed an exposure meter at the McDonald Coudé spectrograph, that has proved most valuable.

Professor Van Biesbroeck has redetermined the positions of the center of the 40-inch dome as follows: $5^{\text{h}}54^{\text{m}}13^{\text{s}}.64$, $+42^{\circ}34'13''.4$, which replaces the value determined in 1897. He also determined the position of the center of the 82-inch dome: $6^{\text{h}}56^{\text{m}}5^{\text{s}}.34$, $+30^{\circ}40'17''.7$. Both values differ slightly from those previously used in the Nautical Almanac.

As a matter of interest the undersigned requested Professor W. L. Libby to determine the age of the water pumped from the McDonald Observatory well since it fell as rain; it was found, from the tritium content, to be at least 50 years old which means that temporary droughts will not affect the supply.

SOLAR SYSTEM

Lunar Studies. Under the sponsorship of an ARDC contract the preparation of the Photographic Lunar Atlas progressed to the point where it could go to press later in 1959. The Atlas consists of 230 sheets 16 by 20 inches, 11 introductory and giving the IAU nomenclature; and 219 of 44 areas in which the visible lunar surface has been divided. The latter are on a scale of 100 inches to the lunar diameter. Printing is to be done by D. F. Keller Co. of Chicago; the publisher is the University of Chicago Press. Photographic programs, both at Yerkes and McDonald were able to supply needed phases of limb areas, in particular, not covered by the existing plate collections. The remaining copying work was done by R. Watson at the Lick Observatory, and

Whitaker, Tapscott and Kuiper at Yerkes. The final selection of the Atlas prints was made by Whitaker and Kuiper. Visual studies with the 40- and 82-inch telescopes were made by Arthur, Whitaker and Kuiper. A selenodetic program was organized by Arthur, based on 40-inch photographs being taken mostly by E. Moore. A beginning was made with the production of rectified lunar photographs of limb areas with the aid of an optical bench and a 3-foot precision hemisphere coated white. No appreciable loss in definition was experienced. Several reports were issued; reference is made to one containing 23 illustrations ("The Exploration of the Moon," *Vistas in Astronautics*, Vol. II, Pergamon Press 1959).

Planetary Surface Studies included the Mars opposition of 1958 when a good series of the satellites was taken with the 82-inch telescope by Kuiper, and visual observations including color studies of the planet were made by Kuiper and Lenham; the Jupiter opposition of 1958 by Kuiper and Lenham; and Venus during the summer of 1959 with the 40-inch telescope by two summer students, Binder and Cruickshank.

Asteroids. The Survey of Asteroids, started in 1950 at the McDonald Observatory, was published in 1958 (*Ap. J. Supplement* No. 32). The frequency curves of absolute magnitude for three distance groups were found to be bimodal suggesting that the asteroids belong to two classes, possibly formed by accretion and collisions, respectively. The magnitudes derived, supplemented by values derived by Gehrels for some 300 more uncertain cases, were adopted by the Moscow 1958 meeting of the IAU for future use in the Asteroid Ephemeris. The observational work on photoelectric light curves was continued by Gehrels under an ARDC contract. Van Biesbroeck measured 30 asteroid positions, all faint objects, requested by the Cincinnati Center.

Polarization studies of the Moon, Venus, Mars, Jupiter, Saturn, three Jupiter satellites, and three asteroids, were begun by Gehrels with his Wollaston photometer. The Moon and Mars show spectacular polarizations in the ultraviolet.

Comets. During the year 1957-58 Van Biesbroeck had 12 comets under observation; he determined 144 positions. Attention was also directed to estimates of brightness and tail structure. The double nucleus of periodic comet Wirtanen (1956c) was still present. The fainter component is trailing; on May 23, 1958 its distance was 20".

During the year 1958-59 Van Biesbroeck kept 10 comets under observation. He obtained 147

plates with the 82- and 24-inch telescopes, mostly for positions, but they included some longer exposures to bring out the physical features. The two nuclei of comet Wirtanen had reached the separation of 25" by the end of 1958. Notable fluctuations again occurred in the brightness of periodic comet Schwassmann-Wachmann (1925 II). It was 13 mag. at the end of August 1958, as faint as 18 mag. September 12, and again brighter (15 mag.) on September 22. It was faint in October and November and rose to 14 mag. on November 29. Van Biesbroeck completed the definitive orbit of the faint comet 1954 i (Van Biesbroeck) including the prediction for the next return in 1966, taking into account the perturbations by Jupiter and Saturn. The period of this comet (12.4 years) differs so little from that of Jupiter (11.9 years) that large perturbations by that planet will occur in time. There was however no near approach during this first revolution. Van Biesbroeck has also started work on the near-parabolic comet 1947 k (Bester) which he followed in 1947-49 for an interval of 500 days.

Earthlight. Van Biesbroeck made measures of the brightness of the earthlight at every opportunity with a Danjon photometer, as part of the IGY program. Settings through 3 color filters are added to direct measures. During 1958-59 he continued this program and made measures on 39 days. He uniformly reduced the material obtained at the six participating Smithsonian stations under the IGY program, awaiting publication of the world meteorological data with which they will be correlated.

Deep-sea Ash. Limber worked with Dr. Edward Anders of the Fermi Institute on the problem of explaining the widespread deposits of deep-sea ash that J. L. Worzel had discovered. Various terrestrial and astronomical possibilities were examined, and further experiments outlined. A note was sent to *Nature* for publication.

Auroral and Airglow Research. Chamberlain and Brandt investigated excitation processes for various emissions in the twilight airglow, including the Na D-lines, the red O lines, N_2^+ first negative bands, and [N] at 5200 Å. Chamberlain and Mrs. Pesch analyzed several IGY patrol spectra obtained at Yerkes and the Shingleton, Mich., station operated by the Project. This study will serve as a pilot analysis for more extensive IGY studies. High-dispersion plates obtained with the 9-inch spectrograph include a spectrum of the airglow in the violet and one of the great red aurora of February 10-11, 1958, also in the violet. Both these spectra resolve

features not heretofore observed. Wallace has completed an analysis of the auroral spectrum; several new identifications have been established and the plate has been analyzed for the rotational temperatures of the molecular bands. Wallace is continuing a program on the systematic observation with a scanning spectrometer of the sodium D lines in twilight in an effort to establish the absolute abundance of free sodium and its seasonal variation at this latitude. Chamberlain and Dr. D. M. Hunten at the University of Saskatchewan have collaborated for the past three years on a program of theoretical and observational study of the sodium airglow. Brandt has also contributed radiative-transfer theory to the program. A series of eight papers under the general title "Resonance Scattering by Atmospheric Sodium" are being published in the *Journal of Atmospheric and Terrestrial Physics*. Chamberlain and Mr. C. A. Smith have analyzed observed intensities of OH in the infrared airglow and discussed these observations in terms of the excitation processes. Chamberlain and Mrs. Straehler are examining the old observing records of E. E. Barnard to see whether aurorae at Yerkes show any preference for a particular time of night, as they do at many high-latitude stations.

Interplanetary Medium. Brandt and Chamberlain have recently published a theoretical study of Lyman α in the light of the night sky observed through rocket instrumentation by a group at the Naval Research Laboratory. The observations were interpreted in terms of the neutral hydrogen abundance in the interplanetary gas. Chamberlain has worked on the problem of the escape of planetary atmospheres and the solar corona from the point of view of reconciling the hydrodynamic and thermal-escape theories. He has computed the temperature and density of ionized hydrogen from the sun to the earth's orbit with this model.

ASTROMETRY

Parallaxes and Proper Motions. Strand, Lenham and Heiser participated in the 40-inch astrometric program, assisted by Burd, Smith and Richter on a part-time basis during the summer months. During the year 1957-58 981 plates were taken for parallax and for mass ratios of binary systems. An additional 93 second-epoch plates were taken for certain selected galactic clusters and of stars with proper motions larger than $0''.30$ per annum requiring more accurate determinations of the proper motions.

Lenham investigated the proper motions of a $\frac{1}{2} \times \frac{1}{2}$ degree area centered on ϵ Orionis. On the basis of seven pairs of plates, with a time interval of 40 years, a slight contraction of the reference frame of 14 stars brighter than the 11th magnitude (visual) was found, amounting to 3×10^{-6} units per year. The data are inconclusive in view of a mean error of 2×10^{-6} units per year.

The internal motions in the clusters h and χ Persei, based upon plates taken with a time interval of 50 years, were investigated by Leibhardt and Franz at the Dearborn Observatory. For each cluster approximately 70 stars were used to determine the plate constants which include terms of the second order. A program has been written to carry out all the reductions to the standard reference system and compute the proper motions on an IBM 650 electronic computer.

Parallaxes were determined for 30 stars, while for a similar number of stars the plate material has been completed and is awaiting measurement. Each parallax is based upon approximately 50 plates.

In connection with this work, Heiser wrote a program for the IBM 650 electronic computer which will reduce the measured positions to the standard reference system, compute the parallax factors, the parallax and proper motions, in 45 minutes for a series of 50 plates with a total of 200 exposures.

Double Stars. During 1957-58 Van Biesbroeck obtained 1232 measures of double stars during two sessions with the 82-inch. Most of these were close pairs requiring the full power of the telescope. During 1958-59 he obtained 1025 measures with the 82-inch and 65 with the 40-inch at Yerkes. Again, they are mostly of close pairs in critical phases of their motion. Mira Ceti is now definitely closing in after being nearly stationary for some 30 years. The period seems to be of the order of a century. Van Biesbroeck collected and discussed all his measures obtained since 1952. Eight new orbits were computed from this material. The results are being published in *Pub. Yerkes Observatory*, Vol. IX, Part II.

Van den Bos, during his stay at the Observatories, obtained 951 measures with the 82- and 36-inch telescopes at McDonald in August-September 1957, published in *Ap. J. Supplement* No. 36, 1959; and thereafter 4198 measures plus 87 negative results with the 82-, 40-, and 36-inch telescopes, being published in *Pub. Yerkes Observatory*, Vol. IX, Part I. He also undertook the re-

duction of 927 earlier measures made by Kuiper at the Lick Observatory; they are being published as an *Ap. J. Supplement*.

STELLAR SPECTROSCOPY

During the year 1957-58 Abt continued his investigation of line broadening in high luminosity stars with a discussion of the Ib super-giants of spectral types A and F. It was found that the line broadening cannot be due to a Zeeman splitting in a hypothetical magnetic field. Also profiles broadened by rotation and by large-scale turbulence (macroturbulence) are indistinguishable. By neglecting the existence of any macroturbulence one obtains maximum rotational velocities. However as in the case of the bright giants, these maximum velocities are too small to be compatible with both rigid-body rotation in super-giants and conservation of angular momentum during evolution of these stars from the main sequence. Two possibilities exist: (1) the Ib supergiants rotate differentially; this leads to a distribution of rotational velocities that is in agreement with the evolution of rapidly-rotating B stars, or (2) loss of angular momentum, probably by mass loss, occurs during the evolution from the main sequence; the resulting shell might be detectable as $H\alpha$ emission.

To investigate the second possibility spectra were taken at $H\alpha$ of many B- and A-type supergiants. It was found that all stars brighter than $M_v = -6$ have $H\alpha$ in emission. The strength of this emission is very sensitive to, and closely correlated with, luminosity. The emission line is accompanied by a shortward absorption component suggestive of an expanding shell.

Spectroscopic binaries seem to be infrequent in clusters; but Abt found a double-lined binary (HD 23642) in the Pleiades. It consists of A0V and A5m stars. The velocity amplitudes (98.1 and 140.6 km/sec) are large enough to admit the possibility that the system is an eclipsing one.

Abt also worked on intermediate-type supergiants at high galactic latitudes. Some have motions such as to indicate that they did not originate in the galactic plane. These stars have abundance peculiarities among the heavier elements and suggest a different composition for interstellar clouds away from the plane.

During 1958-59 Abt worked primarily on the spectra of variable stars. A consideration of the radiation produced by a shock wave in the at-

mosphere of RR Lyrae successfully predicted and correlated the ultra-violet excess, the hump on the light curve at mid-rising light, the hydrogen emission lines, and the hydrogen and calcium absorption lines. Furthermore, after correction for the radiation produced by the shock, the photometry and radial velocities lead to a successful application of Wesselink's method for determining the luminosity of the star.

Dr. Hardie of the Vanderbilt Observatory and Abt studied the 1.3-day variable BL Herculis and concluded that it is a representative example in the general galactic field of the 1-2 day variables in globular clusters. Its light-range (1.2 magnitudes) is far larger than one would expect for classical Cepheids of this period. Abt obtained a new radial-velocity curve for the 1.95-day classical Cepheid SU Cassiopeiae.

The 4.47-day classical Cepheid FF Aquilae was found by Abt to be a single-lined spectroscopic binary with a period of 1435 days. Cepheid binaries are rare; only four are now known although the radial velocities of about 200 Cepheids have been studied by Joy, Stibbs, and others. This frequency of binaries is compatible with the evolution of Cepheids from B stars (which are frequently in binaries) only if the close B-binaries do not evolve into supergiants and Cepheids.

Gordon Grant's studies of the eclipsing binaries Lambda Tauri and RW Tauri were prepared for publication by Abt after Grant's sudden death. Grant found spectroscopic evidence for the secondary star of Lambda Tauri and obtained radii, masses, and spectral types of both stars. His U , B , V photometry of RW Tauri shows evidence of the gaseous ring around the primary star. New dimensions and masses are obtained; the former show that the K subgiant is not spherical but ellipsoidal with three different radii. The well-defined variation with a period of 61 years in the residuals of the epochs of primary minimum were analyzed as a light-time orbit about a third body, but the resultant mass for the third body is unexpectedly large. Abt and Van Biesbroeck considered whether the 12th-magnitude visual companion could possibly be this third body; their conclusion is that it is not.

U , B , V observations of Zeta Aurigae during ingress of the 1955-1956 eclipse were measured and discussed by Grant and Abt. From these they determined a spectral type (B7) for the secondary star, the intrinsic colors ($B-V = +1.64$, $U-B = +1.84$) of a K4 II star, and—on the assumption that the secondary is a slightly-

evolved main-sequence star—an absolute magnitude ($M_v = -2.2$) for the primary.

Grant and Abt obtained U , B , V photometry of SS Cygni during a 3-magnitude flare. The color variation can be attributed to the variable importance of the visual companion except during rising light.

Abt has studied the spectra of two high-latitude F-type Ia supergiants (89 Herculis and HD 161796) and similar low-latitude ones. The former are at 2.6 and 6.3 kiloparsecs above the galactic plane. To arrive at their present positions in their lifetimes would require initial vertical velocities of 550 and 1350 km/sec. Such velocities are unprecedented; it seems more likely that the stars originated far above the plane and that their compositions indicate the present composition of interstellar material at that position. The stars show underabundances relative to iron by an average of 3 for Sc , Ti , V , and Ni and by a factor of 8 for Zr , Ce , and Eu . Thus the iron peak is much narrower and the elements formed by the s -process are underabundant.

Kraft carried out a search for eclipsing binaries in galactic clusters and O-B associations jointly with A. U. Landolt of Indiana University (*Ap. J.* **129**, 287, 1959). A list of 26 eclipsing binaries that are probably members of clusters was given. These stars may be useful in the determination of a more accurate effective temperature scale, especially among the early spectral types, since their luminosities may be accurately measured by the current methods of cluster photometry. Some preliminary photometric and spectroscopic work has been carried out on QX Cas, in the field of NGC 7790 (in collaboration with Hiltner and Prendergast), but it is not yet certain that the star will prove to be a favorable case, since the spectrum of the secondary is difficult to photograph.

Kraft and Edmonds of the University of Texas, discovered feeble Ca II emission in the spectrum of Procyon (*Ap. J.* **120**, 522, 1959). The measured emission width fits the Wilson-Bappu correlation between the width of K_2 and the absolute visual magnitude; Procyon is thus the first F-type star known to satisfy the correlation.

Kraft made an investigation of the spectrum of Nova DQ Her during the 4^h 39^m eclipse cycle, reported in two papers, one jointly with J. L. Greenstein (*Ap. J.* **130**, 99). The light of the system appears to come mostly from a small shell of material surrounding the nova component, which moves with the nova in the orbit.

The eclipse observed by Walker is really the eclipse of this shell rather than a star in the normal sense. The nova component is probably a white dwarf; estimates of the mass can be made from the white-dwarf theory which agree well with dynamical arguments derived from the width and velocity change of the He II emission line. The most probable mass for the nova appears to be about one-fourth that of the sun.

Kraft reviewed the galactic distance scale derived from Cepheids in a semi-popular article in the *Scientific American* (**201**, 48, 1959).

Jointly with D. C. Camp and W. T. Hughes of Indiana University Kraft carried out an investigation of the time scale for the hydrogen emission lines in population II variable stars (*Ap. J.* **130**, 90). It was found that, if t is the time hydrogen emission is present in the spectra of these stars, $t/P \sim P^{0.25}$ over a range in period from RR Lyr to the high-velocity long-period variables. Considerations of shock waves suggest that, if a common mechanism is responsible for the emission lines in the spectra of all these stars, the mass of a high-velocity long-period variable should be in the vicinity of $1 \odot$.

Kraft was further engaged at the McDonald Observatory in a study of the color excesses of classical Cepheids. By means of a narrow interference filter, the G-band intensity has been measured in Cepheids and supergiants. This spectral feature is sensitive to spectral type in the range of Cepheid variation; the measures are correlated with intrinsic ($B-V$) color from observations of U Sgr and EV Sct, which are members of open clusters, and observations of Polaris and δ Cep, whose colors are derived from companions (*A. J.*, abstract, **64**, 337).

With J. D. Fernie of the University of Cape-town and Hiltner, Kraft made a joint investigation of the O-B association II Pup. It is shown that the classical Cepheid AQ Pup is probably a member of the association; normal colors and an absolute magnitude have been estimated. The object is of special interest because of its long period ($P = 30$ days); however, the southerly declination, faintness of the association stars, and "spread-out" nature of the region make the derivation of definitive results difficult. (*A. J.*, **64**, 331, abstract).

Jointly with Dr. A. Sandage, G. and E. Burbidge undertook a program of long standing in high-dispersion spectroscopy, the measurement of the line blanketing between 3300–6300 Å in a number of normal main-sequence stars,

and one metal-poor star. Mt. Wilson coude spectra were used. First results indicate that the effect of the weak lines in the metal-poor star can account wholly for the ultraviolet excess in the two-color diagram. These results were read at the Liège Symposium July 1959.

THEORETICAL ASTROPHYSICS

Prendergast has found an approximate solution of the equations of hydrodynamics appropriate to the problem of gas streams in close binary systems. The solution reproduces several features of the empirical models which have been constructed to explain the observations. He has also worked on the reduction of rotation curves of galaxies, in collaboration with G. R. Burbidge and E. M. Burbidge.

G. and E. Burbidge published the following papers on theoretical radio astronomy: *Ap. J.* **129**, 849-52, 1959; *IAU Symposium* No. 9, pp. 323-27 and 541-51, 1959. They published a summary on the formation of elements in stars (*Science* **128**, 387-99, 1958) and one on Stellar populations (*Scientific American*, Nov. 1958, pp. 44-50). A major report on Stellar evolution was published in *Handbuch der Physik* **51**, 134-295, 1959.

Chandrasekhar, who during the past years has published many fundamental papers in non-astronomical journals and whose annual reports have been very brief, has summarized his recent investigations for the convenience of astronomers. His report follows in full.

"Since 1953 my time has been divided about equally between the Astronomy and the Physics Departments, and the Enrico Fermi Institute for Nuclear Studies. For this reason, my reports for the earlier years have been no more than a statement of the topics in which my associates and I have been interested. At the request of the Director, I am summarizing below a general account of the areas in which we have principally worked.

"I. *Problems of Thermal Convection.* The onset of thermal convection in layers of fluid heated from below is a classical subject to which the early contributors were Henri Bénard, Lord Rayleigh and Harold Jeffreys. A problem which has interested me very greatly is the extension of this problem to allow for the effects of rotation and magnetic field acting either separately or jointly. The detailed investigation of these latter effects has led to a number of unexpected phenomena: for example, the occurrence of over-

stability in liquid metals when subject to rotation, and of discontinuities which arise from the conflict between the Taylor-Proudman theorem (in the absence of viscosity) and the Cowling theorem (in the absence of resistivity).

"Most of the theoretical phenomena which have been theoretically predicted have been confirmed by laboratory experiments. These experiments were performed by Dr. Y. Nakagawa at the Fermi Institute where under Professor S. Allison's and my supervision a Hydromagnetic Laboratory (under the auspices of the Office of Naval Research) has been set up. A general account of these investigations with references will be found in my Rumford Lecture to the American Academy of Arts and Sciences (*Daedalus* **86**, 323-339, 1957).

"As an extension of the foregoing studies, the problem of thermal convection in fluid spheres and spherical shells has also been considered. The case when the sphere is rotating presents unexpectedly difficult problems. However, some new methods of solving characteristic value problems in high order differential equations which Dr. W. H. Reid (National Science Foundation Fellow at the Yerkes Observatory during 1957) and I have developed enables an effective breakthrough in some of these problems; and Mr. Fred Bisshopp has solved the problem of thermal convection in a rotating fluid sphere in a paper of considerable virtuosity. These papers have largely been published in the *Philosophical Magazine*. Besides Bisshopp, Dr. George Backus has also participated in these investigations.

"II. *The Stability of Viscous Flow Between Rotating Cylinders.* This is a classical problem whose solution by G. I. Taylor in 1922 is one of the landmarks of hydrodynamics. While Taylor solved the underlying theoretical problem to an extent sufficient to clarify the nature of the hydrodynamical instability which arises and further confirmed his theoretical results by some beautiful experiments of his own, it is fair to say that the basic mathematical problem remained unsolved. The nature of the mathematical problem is very different when the gap between the cylinders is small compared to the mean radius of the cylinders and when this is not the case. Taylor's investigation was restricted to the former case; and even in this case the problem was solved only fragmentarily. I have always felt that the solution of this problem presented a challenge and that if one were unable to solve it, then one's hope for solving many of the more

difficult problems of hydrodynamic and hydromagnetic stability were very slim indeed.

"Some years ago in a paper published in the *Mathematika* (Vol. 1, 5-13, 1954), I developed a method by which it was possible to solve Taylor's original problem in a systematic way. More recently by using the techniques developed by Reid and myself it has been possible to solve the general problem in which no restriction on the gap width is made. In order to confirm these newer results, experiments with a precision viscometer have been set up and performed by Russell Donnelly at the Institute of Metals. These experiments not only provide confirmation of the theoretical predictions regarding marginal stability, but also provide valuable new information on the nature of the flow well into the non-linear domain.

"An application of the methods developed in connection with Taylor's original problem has also been made to the problem of mutual friction in the superfluid state of helium (helium II); experiments to investigate the properties of helium II are now being undertaken by Donnelly.

"The related problem of viscous flow in curved channels has been solved by Reid.

"The problem of the stability of viscous flow has also been studied in case the liquid is an electrical conductor and an axial magnetic field is present.

"Most of the investigations relating to these matters have been published in the *Proceedings of the Royal Society*.

"III. *Axisymmetric Magnetic Fields and Fluid Motions*. By starting from a representation of axisymmetric magnetic fields (due to Lüst and Schlüter) in terms of two scalar functions, it was possible to show that the solutions of many problems with axial symmetry can be related to the solution of Laplace's equation in five-dimensional space. With this new technique, several problems relating to force-free magnetic fields, magnetic stars and decay of magnetic fields have been solved by Prendergast, Sykes, Trehan, Reid, Woltjer, Wentzel, and myself.

"A very important advance in relation to these studies has recently been made by Woltjer. By considering attainable equilibrium states as states of minimum total energy compatible with the remaining integrals of the equations of motion as constraints of the system, Woltjer has shown how one can formulate in terms of a variational principle, the solution of the equation of

equilibrium. For example, in the absence of pressure gradients and motions, there is one integral which the magnetic field should satisfy; and the state of lowest magnetic energy compatible with this integral is a force-free state in which the current and the magnetic field are in a constant proportion everywhere. Woltjer has also been able to obtain a complete set of integrals for axisymmetric polytropic magnetic configurations in self-gravitational equilibrium.

"The foregoing account of our work in three of the principle topics by no means summarizes all the investigations of my collaborators during the past years. Only a brief mention can be made of the investigations of Dr. Raymond Hide and myself on the stability of superposed fluids (papers in the *Cambridge Philosophical Society, Proceedings of the Royal Society* and the *Quarterly Journal of Mechanics and Applied Mathematics*); of Professor V. C. A. Ferraro and Dr. Paul Roberts on the reflection and refraction of Alfvén waves; of Roberts on hydromagnetic disturbances in a fluid of finite conductivity (several papers in the *Astrophysical Journal*); and of Miss Guro Gjellestad and Roberts on magnetic stars; and of Trehan on the stability of twisted magnetic fields with motions. And no mention has been made of several papers on the theory of turbulence and plasma physics which I have written in the *Proceedings of the Royal Society*, the *Physical Review*, and the *Annals of Physics*.

"I am now occupied with the writing of a book on *Hydrodynamic and Hydromagnetic Stability* in which I hope to present in a coherent form all of our work relating to this subject.

"After the foregoing excursion into fields only distantly related to current problems of astronomy, it is a relief to be able to say that together with Dr. G. Herzberg, I returned to the quantum theory of two-electron systems sufficiently to recalculate the continuous absorption coefficient of the negative hydrogen ion. On the ground state of helium, Herzberg, Donna Elbert and I have published papers in the *Physical Review*. And two papers on the continuous absorption coefficients of the negative hydrogen ion were published in the *Astrophysical Journal*.

"A cursory examination of even a few of the papers described will show that the investigations would not have been complete without very long and often very difficult calculations. It is fair to record that all the calculations were performed by Miss Donna D. Elbert."

GALACTIC AND EXTRAGALACTIC STUDIES

Galaxy. Hiltner observed the globular cluster M13 with the 82-inch in a joint program with the Palomar Observatory, in the establishment of a photometric sequence to 22 mag. The observations were completed June 1958; the results are contained in a paper written jointly with Baum, Johnson, and Sandage. Iriarte observed 37 blue stars near the North Galactic Pole for *UBV* photometry. In addition to white dwarfs an interesting group of about 10 members fell near $B-V = +0.5$ and $U-B = +0.05$ where the dip in the main-sequence line is caused by the strong *H* lines in A stars. If these stars are on the main sequence their mean distance from the galactic plane is 3600 parsecs.

G. and E. Burbidge obtained stellar spectra for classification in a number of galactic clusters, using the 110 Å/mm camera on the 82-inch cassegrain spectrograph and combined them with results obtained previously at Mt. Wilson. Results for NGC 752, M67, NGC 7789, and M11 have been published. Work on the color-magnitude diagram of NGC 7789, started with Sandage at Mt. Wilson, has also been published.

Hiltner and Iriarte observed a few T Tauri stars for polarization; the large polarization in UX Mon reported by Kron and Hunger was not confirmed. Hiltner also measured the optical polarization of the Cassiopeia radio source; none was found that could not be assigned to interstellar origin.

Extragalactic Systems. Morgan, while Guest Investigator at Mt. Wilson-Palomar in the fall of 1957, devised a modified system of classification for galaxies. It adopts the degree of central concentration of luminosity as the fundamental parameter; this parameter had been found by Morgan and Mayall to be a good indicator of the stellar population of the inner, brighter parts of galaxies. About 600 of the brightest galaxies were classified from plates in the Hubble-Sandage collection. A discussion of the results indicates that there are regional fluctuations within about 40 million parsecs.

Spectrograms obtained by Morgan at McDonald early in 1958 and by Mayall at the Lick Observatory enabled Morgan to draw further conclusions. Two extremes are recognized: (1) "young-star rich" systems (stellar population similar to O-associations and OB open clusters); and (2) "young-star deficient" systems (population similar to highly evolved open clusters and

nuclear globular clusters). The first tend to be irregular in appearance while the second tend to be giant ellipticals and other galaxies having a strong degree of central concentration of luminosity. It is suggested that the first type may be at an earlier stage of evolution than the second—in which large-scale star formation may have ceased in the remote past. The first group may either be younger in age or the two groups are of equal age but pursue their evolution at greatly different rates. Morgan reported on this work at the Solvay Conference.

Later, during a second period as Guest Investigator, Morgan used the original negatives of the Palomar Sky Survey to classify the forms of all galaxies brighter than 13 mag. and north of -25° , there was considerable overlap with the first series. Morgan and Mayall continued their collaboration on the spectra, particularly of irregular galaxies. The discrepancy between the spectrum and the color of NGC 3034 was resolved with the aid of McDonald spectrograms. The galaxy has a spectrum of early type though its color corresponds to a late-type spectrum. The emission lines of *H* and *O* indicate the system to be immersed in a complex of dust, which reddens the starlight and reduces the total light by about 2 mag. The spectrum of the irregular galaxy NGC 4214 was found to resemble the Orion Nebula region, including the presence of *He I* emission lines.

Hiltner observed selected globular clusters in M31 for plane polarization; he found polarization up to 0.05 mag. with the electric vector usually parallel to the plane of the nebula, as is the case for the galaxy. He further observed, with Iriarte, some of the "blue galaxies" reported by Haro. No polarization was observed and there is no evidence that these nebulae have a non-thermal component. In the *B-V*, *U-B* plane these galaxies do not fall in the same area as the T Tauri stars, but rather form a backward (left-upward) extension of the lower part of the main-sequence.

Hiltner's photoelectric measures of the polarization of the jet in M87 essentially confirmed Baade's earlier photographic results. Of the three brightest knots the inner and outer ones are polarized with the electric vector inclined 16° and 9° to the axis of the jet; while the central condensation is polarized at 98° to the axis.

From *UBV* photometry of globular clusters in M31 and M33, presented in a *U-B*, *B-V* diagram, Hiltner found that the globular clusters in M31 resemble those of the galaxy but that those in

M33 are significantly bluer; besides, they are fainter than those in M31. The objects observed in M33 might be rich open clusters rather than globular clusters.

G. and E. M. Burbidge equipped the prime-focus camera of the 82-inch with new metal plateholders and obtained two series of photographs of peculiar multiple galaxies, as well as normal galaxies from the Shapley-Ames catalogue, the Crab Nebula, etc. The Crab photographs were turned over to Dr. Woltjer for a study of the proper motions of the fast-moving wisps of nebulosity discovered by Baade near the central star. A brief discussion of the multiple galaxies was presented at the 1959 Liège Conference. Results published so far are found in *Ap. J.* **130**, 12-14, 15-19, 20-22, 23-25.

They also used the prime-focus B-spectrograph, on one of the peculiar multiple galaxies mentioned; on the multiple galaxy NGC 4676 (as yet unpublished); on NGC 1063, a radio source, for which the rotation curve was derived from the $H\alpha$ emission and the mass determined by a method developed by Prendergast; and on 10 galaxies in the Hercules Cluster (red shift about 11,000 km/sec). The latter were combined with 7 velocities measured previously by Humason, and the stability of the cluster was discussed by means of the virial theorem. The results are to appear in the *Ap. J.* Further, the rotation curve of NGC 2146 (an Sb galaxy) was obtained and the resulting mass distribution jointly derived with Prendergast (*Ap. J.*, in press). A well-determined rotation curve for the Sb-c galaxy M63, extending well past the turnover, was obtained and the mass distribution and total mass were derived jointly with Prendergast. A discussion was made also of NGC 5128, observed earlier. A beginning was made with obtaining data for rotation curves for a number of other galaxies. Two studies have appeared, in *Ap. J.* **129**, 271-281 and **130**, 26-37, 1959, the latter with Prendergast.

G. and E. M. Burbidge also obtained spectra with 110 Å/mm dispersion at the Cassegrain, of a few bright E0 galaxies for the determination of their line profiles, velocity dispersions near the nucleus, and hence the masses. This program is carried out jointly with Dr. Minkowski at Pasadena, who has additional observations, and Prendergast.

Limber completed work on the application of the virial theorem to clusters of galaxies (or

stars) for the case in which a significant fraction of the total mass is intra-cluster gas. A modified form for the expression of the virial theorem has been obtained in this case in terms of the mean square velocity of the galaxies, the total mass of the galaxies, the total mass of the gas, the radius of the cluster, a coefficient depending upon the spatial distribution of the galaxies, and a second coefficient depending upon both the spatial distribution of the galaxies and the spatial distribution of the gas—the two distributions being different in general. The two coefficients have been evaluated and tabulated for those cases in which the two distributions can be approximated by the polytropic distributions with integral indices. It has also been shown how the coefficients corresponding to more general distributions can be approximated by means of the tabulated coefficients (*Ap. J.*, in press).

Finally, Limber has examined the universality of an initial luminosity function based upon the galactic clusters and the solar neighborhood with regard to its implication for the mass-to-light ratios for stellar systems. For this purpose, the times that stars spend on and near the main sequence have been derived as functions of stellar mass from a discussion of the available data for individual stellar models. These results have been used to calculate upper limits to the mass-to-light ratios for stellar systems as functions of the age of the system—on the assumption that an initial luminosity function of the usual form has been operative. The observational data relating to the mass-to-light ratios for galaxies and globular clusters have been obtained. These observational values have been compared with the calculated upper limits, and it has been found that ages greatly in excess of 12 billion years would be required for many galaxies in order that the data be consistent with the adopted form for the initial luminosity function. The evidence appears to support strongly the view that the form of the initial luminosity function has at times differed in a very significant way from its assumed form. It follows that the form of the initial luminosity function is sensitive to at least certain of the physical parameters that describe the pre-stellar medium—parameters such as density, temperature, turbulent and magnetic state, and chemical composition (*Ap. J.* in press).

GERARD P. KUIPER, *Director*

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